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ASCENT CONTROL STUDIES OF THE 049 AND ATP PARALLEL BURN SOLID ROCKET MOTOR SHUTTLE CONFIGURATIONS

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16. ABSTRACT

The control authority approach is a major problem of the parallel burn solid Shuttle configuration due to the many resulting system impacts regardless of the appraoch. This report discusses the major trade studies and their results, which led to the recommendation of an SRB TVC control authority approach.

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DEFINITIONS

MOSES	moments by optimum selection of engine systems
SRB	solid rocket booster
TVC	thrust vector control
FPR	flight performance reserve
GLOW	gross lift-off weight
$q\beta$	load indicator
$C_{\ell\beta}$	rolling moment coefficient due to sideslip angle
HO	hydrogen-oxygen
SRM	solid rocket motor
ASRM	Avanti solid rocket motor
ATP	authority to proceed
T/W	thrust to weight ratio
C_1	aerodynamic disturbing moment coefficient
C_2	control authority moment coefficient
δ_{y1}	engine 1 yaw deflection
δ_{y2}	engine 2 yaw deflection
δ_{y3}	engine 3 yaw deflection
δ_R	rudder deflection
δ_p	pitch deflection
ϕ	roll angle

DEFINITIONS (Concluded)

ψ	yaw angle
β	sideslip angle
ME	main engine
DDT&E	design, development, test and engineering
LOX	liquid oxygen
T_S	solids thrust
T_{ME}	main engine thrust
SSME	space shuttle main engine
a_{0y}	control gains
b_{0y}	control gains
c.g.	center of gravity
NAR	North American Rockwell
MEOP	main engine operating pressure
L/D	length to diameter ratio
RSS	root sum square
H	vertical rise

TECHNICAL MEMORANDUM X-64720

ASCENT CONTROL STUDIES OF THE 049 AND ATP PARALLEL BURN SOLID ROCKET MOTOR SHUTTLE CONFIGURATIONS

INTRODUCTION

The major issues involved in the control authority question, as shown schematically in Figure 1, have remained unchanged since the conceptualization of the configuration; however, the analysis of the many different configurations and a better understanding of the overall interacting phenomena have resulted in: (1) quantifying some of the issues, and (2) gaining insight into or uncovering additional factors that will influence the choice. The basic decision for SRB TVC or No TVC must be made, however, without complete quantification of certain driving issues. These data cannot be obtained until the configuration has settled and this can be accomplished only with detailed, long term analysis.

All of the items listed in Figure 1 are highly coupled and relate to or influence the answer; however, during the course of the studies a few predominant questions have evolved that transcend the trades as indicated. As an example, two characteristics of the vehicle are of paramount importance if the vehicle flies without SRB TVC: (1) the level of the misalignments of the SRB thrust vector, and (2) the aerodynamic characteristics, which include static stability, aero surface effectivenesses, and aeroelastic effects. The major concerns in both cases are the level of uncertainty and the ability to determine statistically this level.

Thus, two choices are open to management if the goal to fly without SRB TVC is realized: (1) demonstrate acceptability through costly testing and analysis, or (2) accept (without demonstration) that predictions are accurate, and accept the associated failure risk. This last option raises the hardest question to answer: What happens if the thrust misalignment is greater than that expected for a given flight, or that the aerodynamic surface effectiveness is less than predicted and cannot efficiently be increased? The difficulty in obtaining these answers is obvious when one realizes the sensitivity of the vehicle performance to initial pitch rates, the marginality of the control system, and the number of various combinations of wind speed, direction, and gust in the presence of SRB misalignments that require analysis. The analysis of these many combinations requires thousands of runs and a firm configuration to obtain the answer.

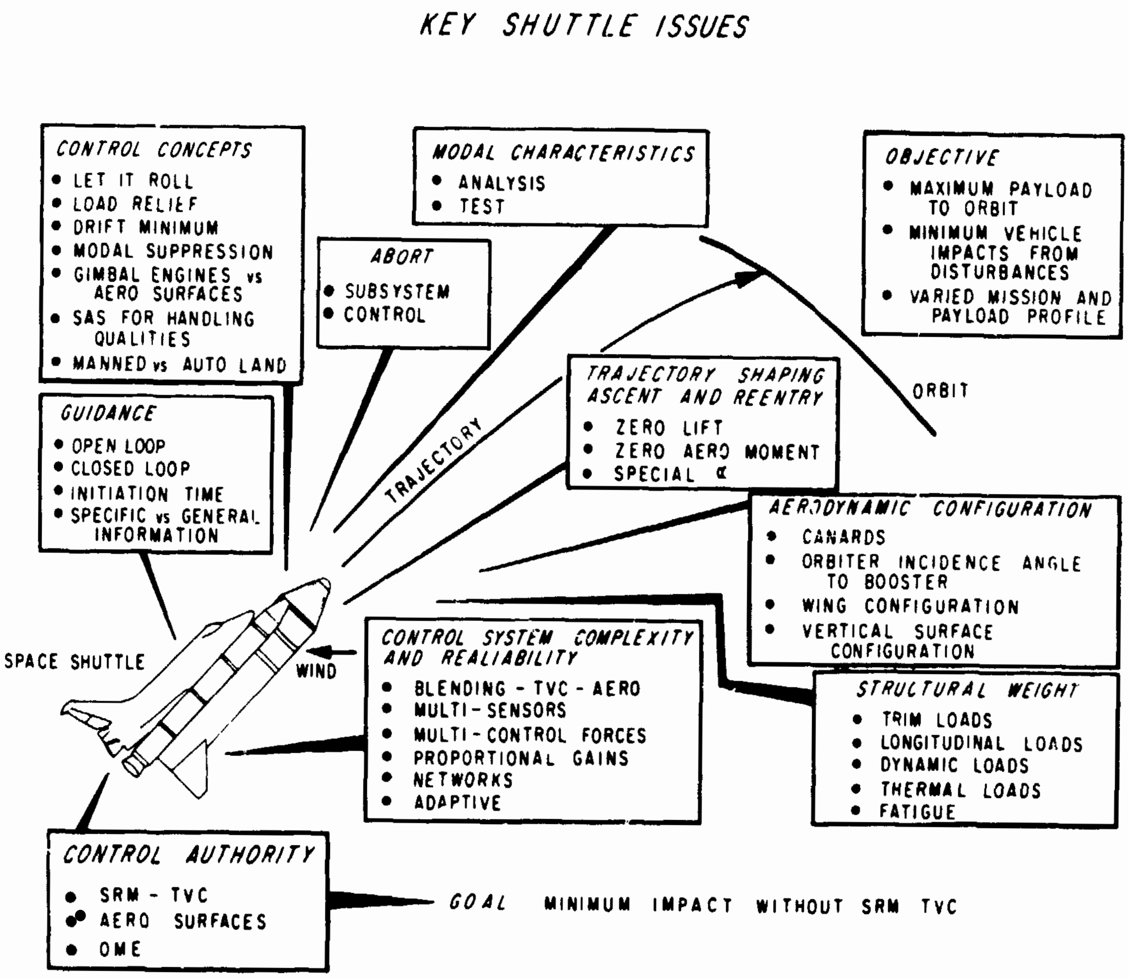

Figure 1. TVC vs no TVC study approach.

Included in this analysis must be the abort system. Of particular importance to the abort system, design, and reliability, is the identification of abort cues for initiation of abort sequences. This identification of proper abort cues is very complex for the no SRB TVC case and large SRB misalignments. This is because of the fast time-varying characteristics of the vehicle, such as mass and aerodynamics, which introduce vehicle states (roll angle and rates, $q\beta$, $q\alpha$, etc.), comparable in magnitude with those associated with the larger SRB misalignments. Since these vehicle state values are of equal size, it is almost impossible to separate the natural signal from an overly large SRB misalignment introduced state. A further complication arises from the nature of SRB misalignment introduced vehicle states. These misalignments can be in any direction; therefore, the vehicle response can be in any direction, making proper detection difficult. In contrast, the states, due to commanded maneuvers, are predictable and can be accounted for.

Another highly significant problem evident on this vehicle is the requirement for modal stability using orbiter only control. Preliminary studies have indicated that modes with large SRB motions cannot be stabilized without SRB TVC. This adds another dimension to the risk question since accurate assessment of this problem can only be made after good aerodynamic force distribution and interference aero forces are determined.

The time deadline of the decision negated the indepth analyses necessary to quantify all aspects of the problem, thereby forcing only basic trend studies which require judgement and extrapolation to arrive at an answer. Furthermore, it has not been possible to develop the very technical analysis techniques that are needed to optimize the design and trade comparisons. For example, the strong coupling between structure, control, and trajectory requires a good optimization program to insure a minimum GLOW, minimum risk vehicle, but this approach is still in development. The same is true of an integrated analysis of lift-off through separation, including combining high angle of attack flight due to lift off winds and low vehicle velocity with the moderate angle of attack flight due to ascent winds and increased vehicle velocities, including control logic, control authority limits, loads constraints and FPR losses.

Another consideration for a completely fair trade between SRB TVC and no SRB TVC would require two separate designs, each of which would be optimized for that approach. Again this was not possible, due to the time constraint. With these limitations in mind, the data presented in this paper were obtained by using the best combinations of analysis techniques available within the time frame. These techniques have utilized trade studies in: (a) trajectory and performance, (b) lift off dynamics, (c) high q response, (d) separation, (e) malfunction dynamics, and (f) elastic body dynamics. The best solution was obtained by using the optimum from one area as the baseline in the next, or merely by using the results of one to extrapolate factors to add to the other. Although these shortcomings -- of limited time, lack of two separate designs, and use of more detailed system studies -- should be recognized, they have for years resulted in adequate (not necessarily optimum) design and should do so in this case.

In summarizing the basic issues, it appears that the major questions, at this time, are: (1) What are the flight risks involved if SRB TVC is used versus the risks involved if it is not used, and (2) since cost difference is very critical, what are the cost risks involved? This report will: (1) state the basic vehicle characteristics, (2) discuss the basic problems and trades, (3) present data to develop trends from these trade studies, (4) make

recommendations pertaining to the overall decisions, and (5) formulate future plans needed for each decisive option development. In order to meet the needs of the diversified interest in the basic question contained, the report is divided into three sections. Section one, the Executive Summary, discusses the basic problems, the trade factors, a summary of trade studies and trends, and recommendations. Section two provides the indepth background information desired by the dedicated technical personnel. Section three contains configuration data and background trade studies that have been conducted to establish trends and baselines.

I. EXECUTIVE SUMMARY

To arrive at an answer to the question under consideration, at least five basic conditions must be met by the Space Shuttle system to accomplish its mission objectives: (1) the dynamic system must be stable, (2) there must be adequate control authority, (3) it must contain sufficient flight performance reserves to meet end conditions under off nominal conditions, (4) the system must stay within the design load envelope, and (5) the system must meet adequate initial conditions for separation. Conditions (1) and (2) would appear to be redundant; however, for an aerodynamically stable vehicle, such as the Shuttle, it is possible, with sufficient additional performance reserve, to meet objectives without control authority. However, the total GLOW and cost increase for this approach, in general, places constraints on the control authority and requires a fairly orderly path control. Establishing the criteria for what is an adequate control authority level is complicated. Flight path deviations due to lack of complete control should not consume more than half the allocated FPR value (3,000 lbs payload) and allow 2° on each main engine for elastic body stability while allowing use of orbiter aero surfaces to their reentry and flyback design value. The loads criteria are the flyback design values. Exceedances of these load values provide impacts to the system. Using these flyback design values as a base, the various vehicle systems are impacted in terms of weight, cost, and payload for both TVC and the no TVC case. One very important conclusion from these preliminary trade studies is that no parallel burn configuration (at the time of the study, using a vehicle like the NAR proposal) had been designed that could meet all five of these flight objectives without significant changes (fins, design of orbiter aero surfaces, load capability FPR) with or without TVC on SRB's. Present configurations with TVC do meet these requirements. This statement is valid without consideration of elastic **body stability and loads.** The present design is based on rigid body loads and control system requirements. Consideration of elastic body effects will increase the vehicle design loads and the control system complexity. The basic system factors involved

1. TVC SYSTEM

   ACTUATION
   POWER
   NOZZLE
   SEAL

2. AERODYNAMIC SYSTEM

   - SHROUDS
   - FINS
   - HINGE MOMENTS
     ENGINES & AERO SURFACES
   - BASE AREA
   - SURFACES
     ACTUATION
     POWER

3. PERFORMANCE

   - CANTS - SRB AND M.E.
   - WINDS - LOAD RELIEF VS. LOADS
   - DRAG FROM USING SURFACES
   - COSINE LOSS OF GIMBALED ENGINE
   - DRAG FROM SHROUD

4. LOADS

   - CANT
   - WINDS
   - HOLDDOWN
   - SHUTDOWN AND SEPARATION

5. SEPARATION SYSTEM

   - FORCE (NO. ROCKETS)
   - LOGIC

6. SRM

   - MISALIGNMENT ACCURACY
   - MISALIGNMENT DEMONSTRATION
   - THRUST SHAPING
   - $T/W = (T_s + T_{M.E.})/W$

7. ABORT CONSIDERATIONS

   - ROCKET ELIMINATION
   - M.E. ENGINE OUT
   - FAILURE MODES

8. CONTROL

   - MODAL SUPPRESSION
   - LOAD RELIEF VS. NO LOAD RELIEF
   - INTERFACES
   - CONTROL AUTHORITY

9. RECOVERY

10. WIND TUNNEL TEST

11. ORBITER SYSTEM

12. OPERATIONS

Figure 2. Factor SRM TVC vs no TVC.

in the trades are listed on Figure 2. Due to their importance in answering the question under consideration, each one will be discussed. For detailed data, one must see sections II and III.

Item 1 of the figure, "The SRB TVC System," only applies to the SRB TVC case but has three key factors: the development of a movable nozzle and seal, the determination of actuation requirements, and the determination of power requirements. The nozzle and seal development requirement is independent of whether the system is used as a full dynamic control device or as a trim device. However, actuation and power are strongly influenced by the usage approach. This raises the question of whether to use SRB TVC fully or as a trim device. Item 2 is highly dependent upon the TVC questions. With TVC, shrouds are required for reducing engine gimbal hinge moment. No TVC possibly requires addition of fins and heavy use of aero surfaces for control while SRB TVC could reduce orbiter main engine gimbal requirements and thereby reduce hydraulic requirements, engine spacing, orbiter base area and weight, thus helping the flyback trim problem and reducing engine cost. Performance (item 3) is strongly influenced by the SRB nozzle cant, which can be relaxed with TVC, thereby allowing reduced GLOW or increased performance. The amount of usage of control effectors has a performance impact, as do wind effects on control authority versus loads. Item 4 lists potential changes in loads due to TVC versus no TVC, such as cant loads, placement of HO LOX tank, holddown approach, SRB lateral and longitudinal placement, etc. Here it should be pointed out that these are some of the major areas where the two independent design approaches discussed in the introduction would be very effective but could not be carried out because of time. Separation rocket requirements (item 5) are a function of the side loads (nozzle cant), as well as the separation logic. As mentioned earlier, the SRB misalignments are critical for the no TVC case and become drivers in quality control, demonstration testing, and control authority requirements, as well as lift-off requirements. Abort considerations (item 7) are important in answering the risk question of larger than predicted misalignments, as discussed earlier. Major issues here are whether SRB TVC increases abort capability and whether the near pad abort rockets can be eliminated. Item 8 lists the control questions: Can modal suppression be provided without SRB TVC? What are the subsystem interface impacts? And the ever present question, what control authority is required? Item 9 raises the question of SRB TVC impact on recovery, while item 10 raises the question of how many extra wind tunnel tests are required without SRB TVC since additional tests are required for determining the aero control surface effectiveness and aeroelastic data more accurately. Orbiter system impacts (item 11), such as increased wing weight required to use aero surfaces, are high cost items because one pound of orbiter weight increases the GLOW by a factor of 40 or more. Item 12 raises the persistent question of operational requirements for the different systems.

In attempting to arrive at these impacts, several problems exist, as shown in Figure 3. The starred items in the figure show major problems for the no TVC case, while the unstarred items are major concerns for either case. At lift-off (item 1), aero surfaces are not effective; therefore, practically all the control authority capability is required to trim the presently predicted SRB misalignment errors of 0.5° which are assumed to generate 3σ misalignment moments on the vehicle. Surfaces do become effective very early and help overcome this problem if their effectiveness is predicted and they can be used. This marginality, without aero surfaces, is illustrated in Figure 4 where these 3σ disturbance moments are plotted along with the control authority capability for full 10° and for 8°. The difference is reserved for dynamics.

All this occurs in a region where the vehicle must start pitching and rolling to one of its varied launch azimuths. If proper initial pitch rates and, within reasonable time, proper vehicle roll are not accomplished, performance losses occur. The ATP configuration trajectory, which has max q occurring at 38 sec., does not have a severe problem since aero surfaces become effective early enough (10 sec.) to increase the control authority available. Other problems exist, however, with the early q, such as spending much longer flight times at high q.

Effective growth potential of the system exists only through increased SRM size and thrust.[1] All past space vehicles have always had growing pains due to expanding requirements and uncovered problems; therefore, growth appears a certainty. With growth (increased SRB thrust) the marginal control condition at lift off can only become worse for the same misalignment conditions.

Without TVC, orbiter aero surfaces must be used extensively; therefore, their effectiveness is very critical to SSME control authority requirements and for control of roll excursions. The differences are shown on Figure 5 in the ATP predicted and the measured effectiveness values. Because of the misalignment condition illustrated in Figure 4, this error in prediction could mean the difference in having a satisfactory versus unsatisfactory solution. Wind tunnel tests showed predicted effectiveness to be high by about 30 % - 50 %.

The vehicle sensitivity to SRB misalignments is very critical. (Item 3 in Figure 3 lists the sources.) Figure 6 shows the effect of roll rate as a function of misalignment while Figure 7 is a plot of $q\beta$ (load indicator) for the same misalignments. Both plots have a sharp increase between misalignments of 0.5° and 0.6°, exceeding acceptable limits. Roll rates above 15°/sec and $q\beta$ above 4500 PSF deg. It should be pointed out that q goes from the 5100 design value to the 1.4 safety factor limit of 7140

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1. Douglas L. Blackwell, Size Analysis of the 156 Inch Diameter EHOT Configuration, IN-AERO-6-72-1, August 31, 1972.

*1. INITIAL TRAJECTORY SHAPING IN PRESENCE OF SRB MISALIGNMENTS:

A. PITCH TILT
B. ROLL TO LAUNCH AZIMUTH
(MAINLY PROBLEM FOR NO SRB TVC SYSTEM SINCE AERO SURFACES ARE NOT EFFECTIVE.)

*2. UNCERTAINTY IN EFFECTIVENESS OF AERO SURFACES:

A. AEROELASTICITY	45-50% REDUCTION
B. PLUME	ESTIMATES VARY - 0 → 50%
C. LOW MACH NUMBERS	

*3. HIGH SENSITIVITY TO ALIGNMENT ERRORS WITH NO TVC SYSTEM.

A. MECHANICAL ALIGNMENT OF SRB TO ET
B. STRUCTURAL DEFORMATION OF SRB AND ET
C. GAS DYNAMICS

*4. CONTROL AUTHORITY LIMITATIONS.

5. STRUCTURAL LOAD IMPACTS VS. PERFORMANCE LOSS. (BASIC PROBLEM REGARDLESS OF APPROACH.)

6. ABORT REQUIREMENTS, APPROACH, AND SYSTEM.

7. LARGE AERODYNAMIC STABILITY AND YAW ROLL COUPLING.

*MAJOR PROBLEMS FOR NO SRT TVC CASE.

Figure 3. Major problems.

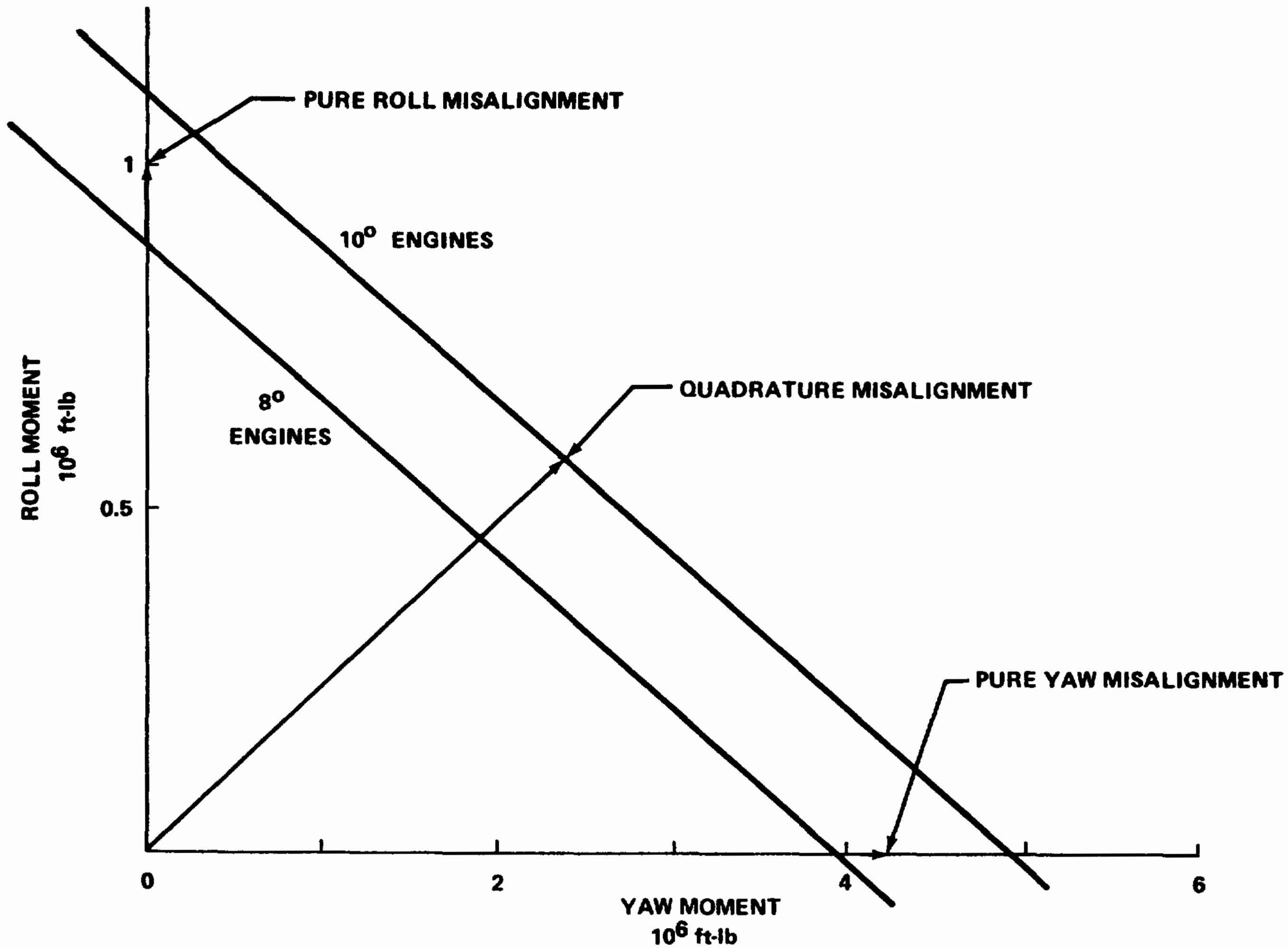


Figure 4. Engine capability and SRM misalignment torques at time = 0.

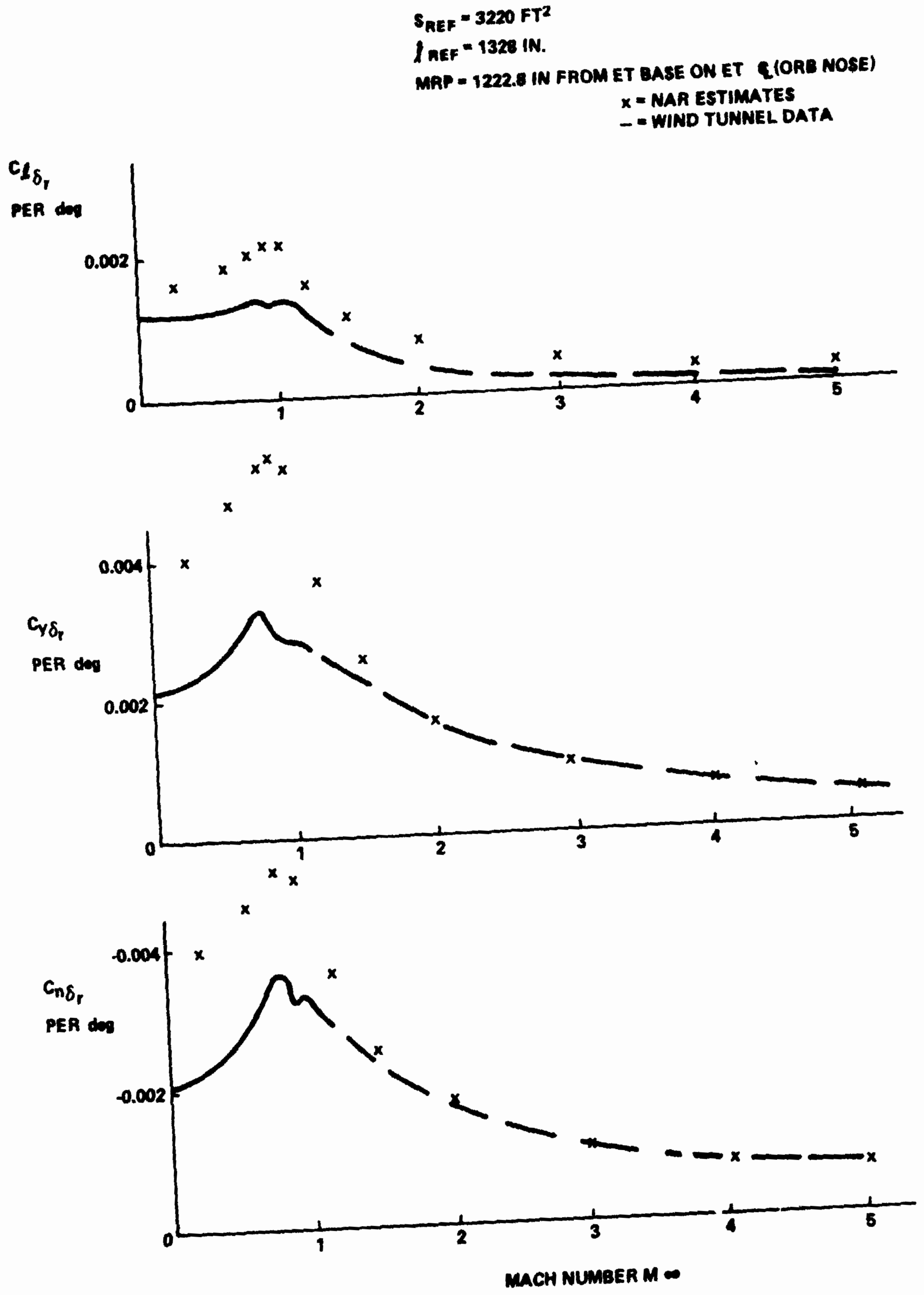


Figure 5. Predicted and wind tunnel surface effectiveness comparisons.

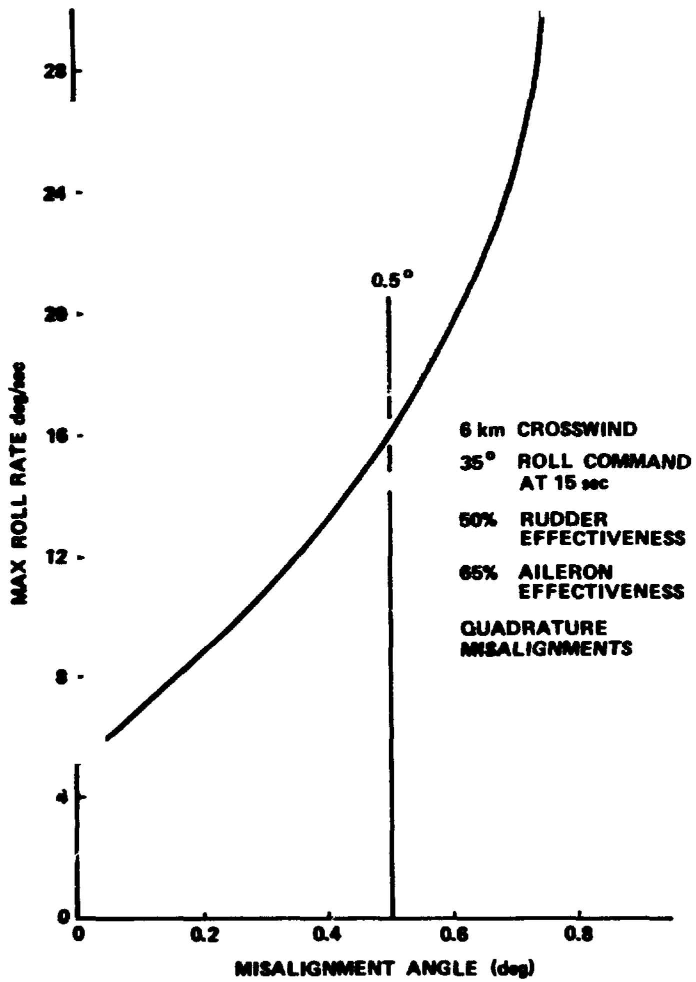


Figure 6. Maximum roll rate response to misalignments.

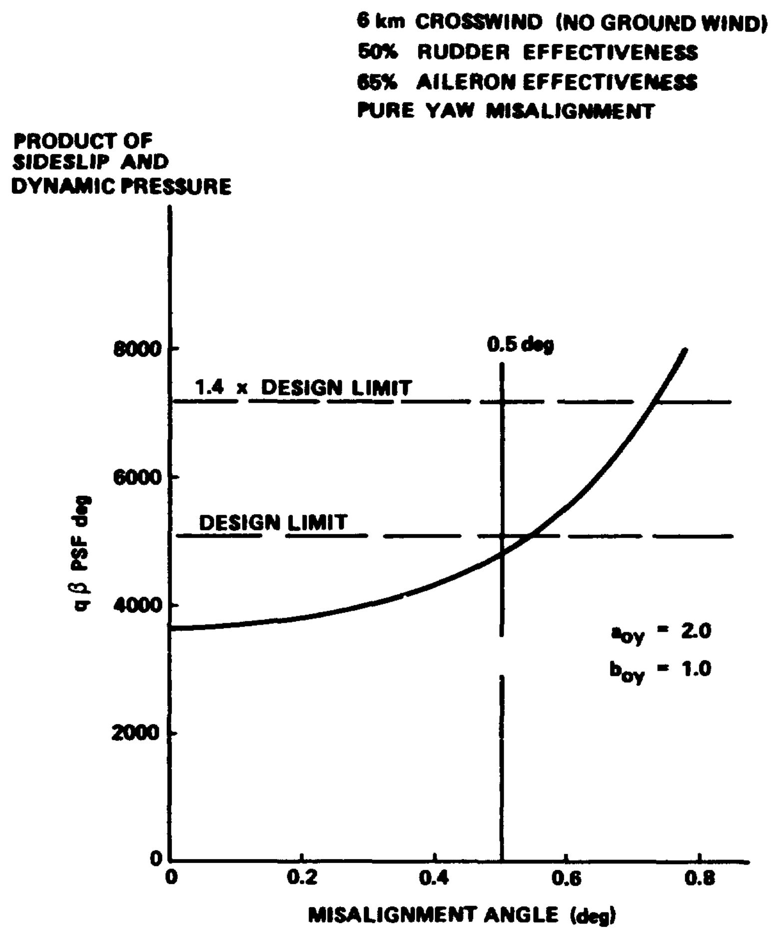


Figure 7. Maximum $q\beta$ response to misalignments.

in less than three seconds for the 0.6° misalignment case, indicating that safe abort would be hard to accomplish, due to potentially short warning times. Also abort cue identification is an obvious problem because of the high roll rates and $q\beta$'s produced from winds and smaller misalignments alone. The control authority limitation of the no TVC case (item 4) has already been discussed.

An ever present problem for all Shuttle concepts is the trade between structural loads and performance. If tight path control is enforced, structural loads are high due to the large induced angle of attack. Reducing angle of attack turns the vehicle into the wind, thus creating large attitude errors and performance losses. The best answer is, in general, a compromise bet[illegible] the two. Abort requirements, approach, and system (item 6) are critic[illegible] problems, but beyond the scope of this paper. Present configurations (i[illegible] 7) have large aerodynamic stability and yaw roll coupling, which compound the problems discussed under control authority and loads and performance trades. The best ascent design would have small aerodynamic stability with the magnitude of C_{ℓ_β} such that the combined yaw roll moment vector would be nearly collinear (that is, produce the same ratio of roll moment to yaw moment) with the total control authority vector (see section 2).

Figure 8 lists the system requirements and potential relaxed constraints for the SRB TVC case and the no SRB TVC case. This chart is a summary and contains many of the issues previously discussed. It should be reemphasized here that the potential rel[illegible]xed constraints listed for the TVC case are not based on a vehicle designed to take full advantage of the incorporation of TVC but [illegible]re listings of the major items seen at this time. The key differentiators between SRB TVC and no SRB TVC are: (1) the requirements for stringent control of SRB misalignments, (2) accurate prediction of aero dynamic surface effectiveness, (3) the large performance loss resulting from SRB nozzle cant, and (4) the cost of the SRB TVC system itself. The first three penalize the no SRB TVC system, whereas the last item is an SRB TVC system penalty, but only a slight penalty when considering the total systems costs with and without TVC.

Figure 9 summarizes the trades listed in Figure 2 in terms of cost and GLOW for both TVC and no TVC. A detailed breakout of these items is presented in section II. The TVC cost is based on 5 reuses of the system and includes refurbishment. The cost is given in terms of '71 dollars. The SRB TVC system that is priced is for a one deg sec rate system at ± 5° deflection. [illegible]our separation rockets can be eliminated due to the reduced cant for the TVC case. The cant effect alone saves 70,000 lbs GLOW per flight; but the

SRB TVC

REQUIREMENTS

1. MOVABLE NOZZLE
2. ACTUATION SYSTEM
3. SRB - ORBITER CONTROL INTERFACE
4. AERODYNAMIC SHROUD AROUND NOZZLE
5. INSTRUMENTATION

RELAXED CONSTRAINTS

1. SRB CANTS
2. SEPARATION ROCKETS
3. MISALIGNMENT TOLERANCES
4. SRB REGRESSION RATE
5. SIMPLE MIXING LOGIC TO EFFECTORS
6. NO AERODYNAMIC FIXES
7. INCREASED ABORT CAPABILITY
8. POTENTIAL M.E. GIMBAL RANGE DECREASE

   049 $\pm 2°$ YAW

   ATP $\pm 2°$ YAW

9. POSSIBILITY OF PINNING AILERONS DURING ASCENT FLIGHT
10. LONGITUDINAL SRB LOCATION

NO SRB TVC

REQUIREMENTS

1. STRINGENT SRB MISALIGNMENT CONTROL AND DEMONSTRATION
2. AERODYNAMIC FIXES (FINS)
3. SRB YAW CANT THROUGH BURNOUT C.G.
4. LARGE NUMBER OF SEPARATION ROCKETS TO CANCEL SIDE FORCES
5. INCREASED DUTY CYCLE ON ALL CONTROL SYSTEMS
6. INCREASED WIND TUNNEL TESTING

RELAXED CONSTRAINTS

ORBITER SRB INTERFACES

Figure 8. SRB TVC and no SRB TVC requirements and relaxed constraint.

	TVC GLOW	TVC COST	NO TVC GLOW	NO TVC COST
1. TVC SYSTEM	+29,000	+121 (M)		
2. SEPARATION ROCKETS	-10,500#	- 43 (M)		
3. CANT EFFECT	-70,000	- 60 (M)		
4. ENGINE SHROUD	+56,000	+ 88 (M)		
5. FINS			+10,138	+47.4 (M)
6. TEST FACILITIES DEVELOPMENT AND CHECKOUT				+16 (M)
7. SRB DEMONSTRATION				+60 (M)
8. OTHER				
TOTAL:				

TVC SYSTEM COSTS 24 (M) **LESS THAN NO TVC SYSTEM.**

Figure 9. Summary (cost), GLOW and cost Δ's from baseline.

gimballing engines must be protected from the large aerodynamic hinge moment. This costs 56,000 lbs GLOW and \$85M program cost. Due to the large aerodynamic yaw stability characteristics and uncertainty of aero surface effectiveness, fins are required for the no TVC case. These cost 10,000 lbs GLOW and \$47 M. Verification of a 1/2° SRB misalignment for a 99% confidence level requires 30 additional, above the 10 baselined in the program, SRB test firings and more elaborate test equipment. The requirement for the test firings for verification was arrived at by assuming a standard deviation of 0.175 misalignment from test and assuming 99% confidence level using conventional statistical qualification formulas. This cost is \$76 M without accounting for any possible schedule slippage. Additional wind tunnel testing will be required to obtain aero surface effectiveness data, but no estimate is available. Using the surfaces to the extent required to fly without TVC impacts the orbiter flyback weight 2,000 lbs according to NAR. This is not included in these cost data. Based on the assumption that the slow rate TVC system is adequate, SRB TVC saves the program approximately \$17 M (without orbiter impacts or removal of the Abort Solid Rocket Motors (ASRM's)).

The prime conclusion reached is:

Recommend TVC, primarily because of the unknown risks resulting from the uncertainty in SRB thrust vector alignment error and aero surface effectiveness. Also, the following conclusions were made:

1. SRB TVC desensitizes the system so that it is not dependent on highly accurate aero surface effectiveness data and SRB misalignment predictions.

2. SRB TVC allows a more definitive state identification for failure modes and abort cues, including potential abort capability increase.

3. There is marginality of control authority in all flight regimes without SRB TVC.

4. There is better growth potential.

5. There is capability for structural mode suppression by increasing the SRB TVC maximum rate.

6. SRB TVC could eliminate the requirement for control effectors mix logic MOSES and engine stop logic; however, this approach will probably be desirable for the TVC case due to its simplicity and added control authority margins particular for abort.

7. SRB TVC, because of its slow rate, does not, at this time, preclude the need for adaptive control schemes to handle modal stability and modal suppression requirements.

8. SRB TVC is the only control authority approach which does not require a multiple solution. For example, Fins aero surfaces SRB misalignment demonstration .

A. Areas that Need Emphasis

Regardless of the choice of control authority source SRB TVC versus orbiter only control , several areas need extensive analysis, with the no SRB TVC case having additional requirements. These areas will be discussed.

No SRB TVC

A comprehensive discussion of the MOSES concept has been treated in Ref. 2.

The mixer approach, as presented, needs to have added the logic to handle the saturating of control effectors using the best capability of the remaining effectors. This approach also needs modal suppression concepts, as an additional feature.

These developments are mandatory for the no SRB TVC case and are very efficient and useful for the SRB TVC case, particularly for abort considerations.

General

Analyses and techniques that are required, regardless of the choice of SRB TVC or no SRB TVC are:

1. The indepth analysis of the vehicle response to measured winds, which have wind speed, gust, and direction correlated. Elastic body loads are very dependent on these wind inputs and require this correlation to eliminate conservative load estimations. This is of particular importance to the H.O. tank where a high mass fraction is essential.

2. Lift-off and high q dynamics analyses have historically been conducted as special, separate studies. An integrated system analysis is

2. Stephen W. Winder and David K. Mowery, Space Shuttle Control Moments by Optimal Selection of Engine Signal. October 17, 1972.

required as verification of these specialized approaches to eliminate conservatism and insure mission success.

3. A modal suppression requirement study is necessary, but very complicated due to the complex modal properties of many, closely grouped three dimensional modes. These dynamic load levels could possibly design the external tank. Again, the vehicle performance depends on a very low mass for the tank weight and, therefore, these loads must be carefully reduced.

Alluded to earlier in this section was the strong coupling between trajectory, control, and structural design. This coupling requires a combined optimal analysis program. This program is under development and ca at least predict some effective and efficient changes to the baseline system. This analysis is necessary to insure a viable, optimal system and the importance of this approach must not be minimized if the Shuttle is to be capable of meeting its quick launch, variable mission concept.

In summary, regardless of the control authority approach chosen, several delicate technical problems must be evaluated. These are:

1. Measured wind analysis instead of the synthetic profile approach for control system design and loads.

2. Mixer logic and engine saturation logic development.

3. Modal suppression and gust loads requirements.

4. Integrated lift-off-ascent analysis.

5. Structural dynamic modeling.

6. Sensor location analysis for modal stability.

II. BACKGROUND DATA

A. SRB Misalignments

1. SOURCES

As was pointed out in the executive summary, one of the major contributors to the requirement for SRB TVC is the inability to fabricate a twin

solid system that does not have thrust unbalance and thrust misalignments. The thrust misalignments are caused by:

a. Gas dynamics within the nozzle

b. Nozzle misalignment to the SRM

c. SRM stacking error

d. SRM misalignment to the HO tank

e. Static trim elastic deflections

f. Temperature gradients

g. Dynamics and aeroelastic effects.

The problem is compounded because: (a) At a minimum, 80% of the thrust is from the SRM's, (b) the control characteristics of the main engine are not collinear (i.e. they do not produce the same ratio of roll moment to yaw moment) with these SRB disturbance moments, and (c) the large relative moment arm of the SRB's in roll. The memorandum, SP-EM-SE(19)-72, "Solid Rocket Booster Thrust Vector Control (SRB TVC)," [3] contains a presentation on the SRB misalignments and the mass for implementing SRB TVC. The conclusion of this analysis was that the SRB misalignment alone would be less than 0.5° and have a circular distribution. The error sources are given in Figure 10, while the thrust unbalance is shown in Figure 11. A typical misalignment for the Avanti SRM (Fig. 12) shows both a time changing or running mean due to the cant, with a variance about the mean. The mean itself varies 0.5° in its 80 second burn time. Since the cant effect cancels because of its predictability on each engine, only the variance is important to the control requirements problem.

A static trim elastic body error estimate (Fig. 13) has been made using preliminary modes and shows small errors in all cases.

Effective misalignments caused by dynamics of the structure should not affect the control requirements problem, since all modes will have greater than 1.5 Hz oscillations. With this high frequency oscillation, there will be cancellation of effects.

3. Dr. H. Thomason, Solid Rocket Booster Thrust Vector Control (SRB TVC), SP-EM-SE (19) - 72, October 12, 1972.

SOURCE	ANGULAR ERROR (DEG) PITCH PLANE	YAW PLANE
• THRUST MEASUREMENT ERROR (STATE-OF-THE-ART)	± 0.33	± 0.33
• MECHANICAL	± 0.19	± 0.19
• THROAT EROSION, GAS DYNAMICS	± 0.06	± 0.14

Figure 10. ATP SRM thrust vector alignment error assessment (single motor).

TIME INTERVAL	MAXIMUM IMBALANCE LBS
• IGNITION TRANSIENT	300,000
• WEB ACTION TIME	200,000
• TAILOFF TRANSIENT	550,000

Figure 11. NAR ATP solid rocket booster predicted maximum thrust imbalance for a single pair (unmatched).

Static aeroelastic misalignment for both the symmetrical and anti-symmetrical modes could lead to significant misalignment values, particularly for slowly changing wind speeds. Sufficient aero force distributions are not available to make these estimates.

2. SRB TVC SYSTEM

The referenced memorandum[4] contains cost and weight numbers for various nozzle designs and actuation systems. The recommendation was for either a flex or Techroll seal, movable nozzle with pneumatic hydraulic

4. ibid.

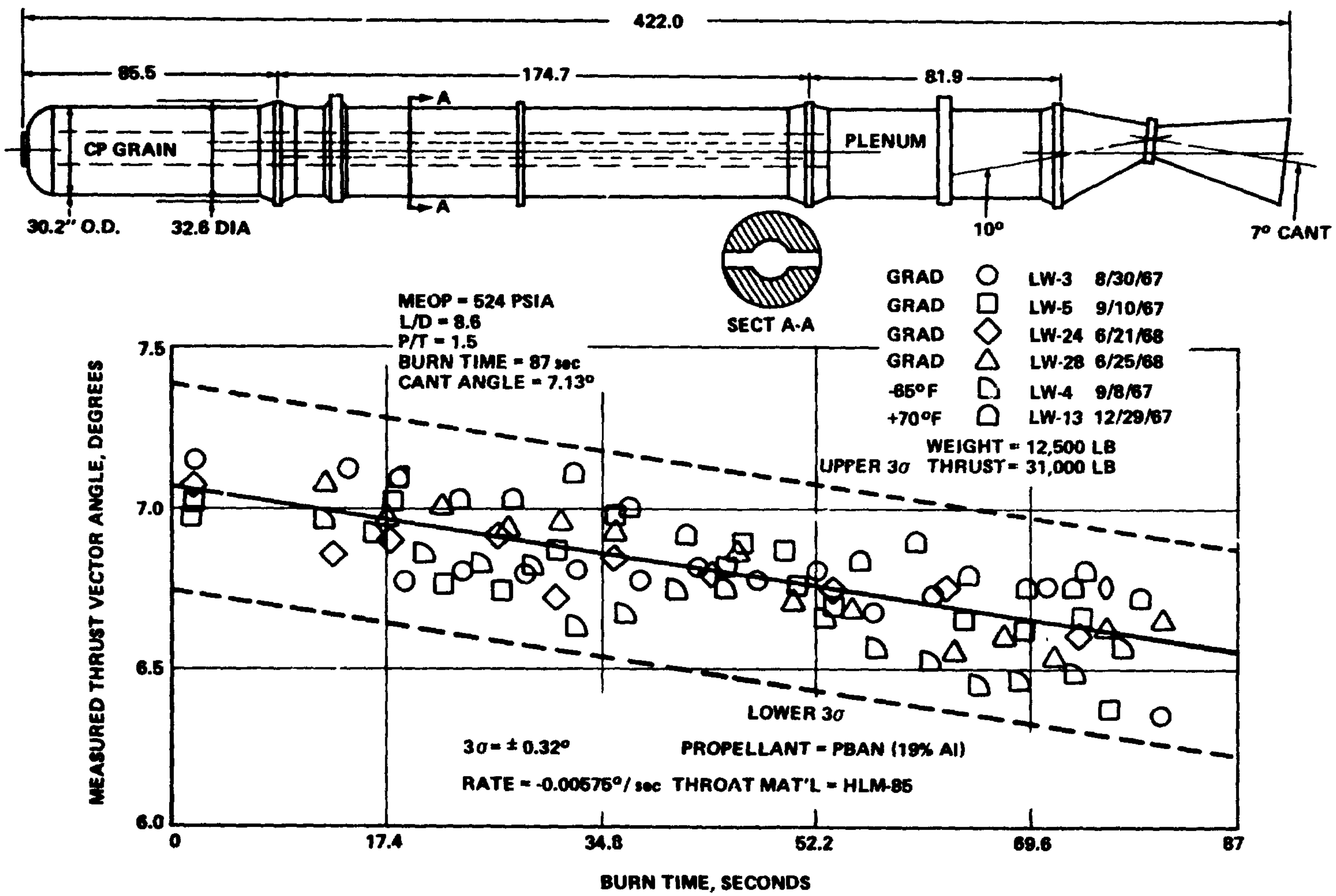


Figure 12. Measured thrust vector angle vs time for Avanti SRM (based on six flight weight motor tests).

GIMBAL RESPONSE TO NOMINAL ENGINE CANT (IN RADIANS)

	ROTATION @ X	ROTATION @ Y	ROTATION @ Z
ORBITER ENGINE	-0.0000299476	-0.0003505276	-0.0000052053
+Y - SRM	+0.0000048777	-0.0005337126	-0.0013473808
- Y - SRM	+0.0000049126	-0.0005352789	+0.0013479423

GIMBAL RESPONSE TO YAW MISALIGNMENT LOADING (IN RADIANS)

	ROTATION @ X	ROTATION @ Y	ROTATION @ Z
ORBITER ENGINE	+0.0001586201	-0.0003495603	+0.0001261306
+Y - SRM	+0.0000021602	-0.0005262516	-0.0013839751
-Y - SRM	-0.0000076285	-0.0005419601	+0.0013112517

GIMBAL RESPONSE TO ROLL MISALIGNMENT LOADING (IN RADIANS)

	ROTATION @ X	ROTATION @ Y	ROTATION @ Z
ORBITER ENGINE	+0.0001474468	-0.0003500288	-0.0000235431
+Y - SRM	+0.0000253302	-0.0005531520	-0.0013405629
-Y - SRM	+0.0000155399	-0.0005158747	+0.0013547190

Figure 13. Three tables showing gimbal response.

actuation. The weight of the two systems is approximately the same. The cost of these systems ($121M) was based on a detailed in-house study (Astronautics Laboratory) and a survey of the major solids contractors.

3. DEMONSTRATION

Man rating of vehicles, in general, requires that potentially dangerous phenomena be accurately known. Obtaining this knowledge is the major problem for the no SRB TVC system. For example, if it was desired to have a 0.5° demonstrated misalignment value at a 99% confidence level, then it could be postulated how many firings would be required for a given measured standard deviation. If the standard deviation was 0.12° then 40 firings would be required to demonstrate the 99% confidence level for 0.5° misalignment. This is based on an assumption that these small misalignment values can be measured. With such large longitudinal and lateral (due to 15° cant) forces, some contractors state that it is basically beyond the state of the art to measure the additional force that results from a small misalignment. It was estimated by the Astronautics Laboratory above referenced memorandum that a $16(M) development program would be required to achieve this measurement accuracy in addition to the costs of 30 additional test firings for demonstration. The demonstration problem is eliminated if SRB TVC is used. Present analyses have shown that a 1° misalignment is acceptable with SRB TVC. This misalignment can be demonstrated within the present SRB test firing program plans and using state of the art measuring techniques.

4. ANALYSIS

Assuming that there exists a demonstrated misalignment value with a certain confidence level, the question arises as to how to use this data for paired motors without being unduly conservative. This problem is discussed in document cited in footnote 5 and means are provided for achieving 3σ disturbance moments for different misalignment relationships between the two motors. These basic relationships are summed up in Figure 14, for in-phase and 90° out-of-phase motors, giving appropriate misalignment values to place on each motor to produce the 3σ moments. A plot of these 3σ moments for the worst theta angle was given in the executive summary (Fig. 4). It is clear that the greater the confidence level of the demonstrated misalignment value, the smaller the alignment value that must be used to produce a 3σ moment (see item III, Figure 14). The message here is obvious. If the demonstration program produces confidence levels that are lower than expected, a larger design misalignment sigma level must be used to generate the 3σ moments, or higher risks to the system must be accepted.

5. Mario H. Rheinfurth, Effect of Thrust Vector Misalignment on Control System Design, S&E-AERO-DD-29-72, October 6, 1972.

THRUST MISALIGNMENTS:

I. MISALIGNMENTS IN PHASE OR 180° OUR OF PHASE -- 2.12σ

θ VARIES FROM 0 ⟶ 360°

II. MISALIGNMENTS OF TWO SRM'S 90° OUR OF PHASE -- 1.85σ

θ VARIES FROM 0 ⟶ 360°

III. σ VALUES

	CONFIDENCE LEVEL	σ	2.12σ	1.85σ
0.5° MISALIGNMENT	99.9%	0.135°	0.29°	0.25°
	99.0%	0.165°	0.35°	0.31°
0.25° MISALIGNMENT	99.9%	0.0675°	0.145°	0.125°
	99.0%	0.0825°	0.175°	0.152°

IV. THRUST DELTAS

CORE 4%

Figure 14. SRM misalignment characteristics.

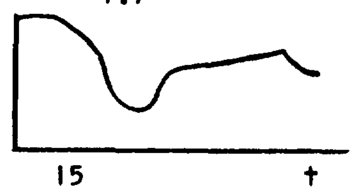
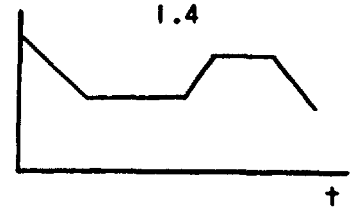
Without SRB TVC it has been assummed in this analysis that a 0.5° SRB thrust misalignment could be demonstrated to a 99% confidence level. For the case with SRB TVC this same value would be 1.0° thrust misalignment and the corresponding σ values in item III, Figure 14, would be doubled.

B. Controllability, Performance, and Loads

Two vehicles were analyzed to determine controllability, performance, and loads characteristics, with and without SRB TVC. The first vehicle was designated 049 (see appendix for configuration) and the second was the NAR ATP vehicle. The 049 work was accomplished between release of the proposal and awarding the contract, at which time the ATP data were available for analysis. The two vehicles are compared in Figure 15 in five key areas that have a major effect on the study results. The thrust to weight ratio (T/W) at lift-off is quite different, 1.4 and 1.7, with the ATP vehicle being the higher value. This increases the effect of SRB misalignments on control authority. Also, the thrust curve of the ATP configuration remains flat for several seconds, while the 049 curve begins immediately to regress. This decreases the effects of misalignments for the 049 configuration as a function of flight time. Dynamic pressure is 125 PSF higher for the ATP vehicle which could lead to higher loads. This larger q and T/W, however, increase the vehicle's injected weight into orbit.

Indicators of the vehicle dynamic characteristics and the control authority requirements are the ratio of the aerodynamic disturbing moment coefficient, C_1, and the control authority moment coefficient, C_2. Only orbiter main engines were used to calculate C_2. Both vehicles are stable in pitch with the same ratio; however, the ATP vehicle has large yaw aerodynamic stability, hence a factor of 3 increase over the 049 vehicle.

This large stability will force either letting the vehicle turn into the wind with the corresponding performance losses, or accepting high structural loads and control authority requirements. The yaw-roll coupling is slightly higher for the ATP vehicle but is a problem for both vehicles since very little roll control authority is available from the orbiter main engines. These large values will force the use of orbiter aero surfaces and possibly an aerodynamic fin or SRB TVC. Finally the 049 vehicle has twin rudders while the ATP is a single rudder configuration. Ailerons have been baselined for use on the ATP vehicle and not for 04 9. With these background configuration differences, the study results will be presented as: (1) Nonaerodynamic regimes (lift-off and tail-off), (2) aerodynamic regions (high q), (3) elastic body requirements,

	ATP	049
1. T/W LIFTOFF	1.7	1.4
2. THRUST SHAPE (SRB)		
3. MAX q	630 PSF .93 M 38 SEC	505 PSF 1.35 M 78 SEC
		NO FINS
4. C_1/C_2 PITCH	1.29	1.29
YAW	1.72	.66
ROLL*	10.94	7.92
5. AERODYNAMIC SURFACES	SINGLE RUDDER AILERONS USED DURING ASCENT	TWIN RUDDERS NO AILERONS USED DURING ASCENT

$$^*C_{1_{ROLL}} = qsb\, C_{\ell_\beta}/I_x$$

$$C_{2_{ROLL}} = (\Sigma F_i\, \ell_i)/I_x$$

Figure 15. Differences in configuration.

(4) mixer concepts, (5) effects of using an integrated lift-off ascent wind profile, (6) abort considerations, and (7) general trend studies important to overall system considerations.

1. NONAERODYNAMIC REGIONS

a. Lift-off. Three separate problems are important at lift-off: (1) tower collision potential, (2) control system saturation, (3) recovering from lift-off transients with satisfactory vehicle states and control authority to achieve the proper trajectory from pitch rate and vehicle orientation. The vehicle orientation is very important since the difference in performance in flying the orbiter head up versus head down is on the order of 3500 pounds of payload. Since the launch pad must be fixed and the vehicle must perform several mission options, a minimum of 35° roll for at least one mission is required to achieve the proper orbiter orientation.

The 049 vehicle had acceptable characteristics in all three areas of concern. Figures 16 through 18 are vehicle state histories as a function of altitude for an RSS combination of major vehicle distributions, lateral c.g. offset, SRB thrust difference, SRB thrust misalignment, and ground winds. The vehicle drift is small and generally away from the tower; therefore, there is no tower collision problem. The engines hit the soft limit but do not hit the 10° hard limit, and the roll angle is acceptable, reaching about 14° at 280 meters altitude. The three different plots, shown for each variable, are different mixing logics, where 033 indicates a yaw-roll uncoupled logic (gimballing about the three engine centroid) and 026 (gimballing engines about the approximate centroid of the two bottom engines) uses increased roll authority at the expense of yaw control. If early drift is a problem, then the 026 logic would be needed; however, this leads to drift problems and trajectory shaping problems since the problem of trimming out misalignments is merely shifted from near pad to a higher altitude.

The ATP had much more severe lift-off problems due to the higher T/W and could be made but marginally acceptable only through the early use of aero surfaces. Figure 19 is a plot of the maximum roll torque due to SRB thrust misalignments and the available roll torque from rudder and ailerons from the ATP vehicle. After approximately 10 seconds, there is sufficient aerodynamic control surface torque to start trimming the vehicle; however, the control engines do saturate until this time and roll angles build up. Figures 20 through 22 are the same type charts as presented for 049, indicating the more severe problem of recovery of controllability as aerosurfaces become effective. If aerosurface effectiveness is lower than predicted, controllability and trajectory shaping problems would occur.

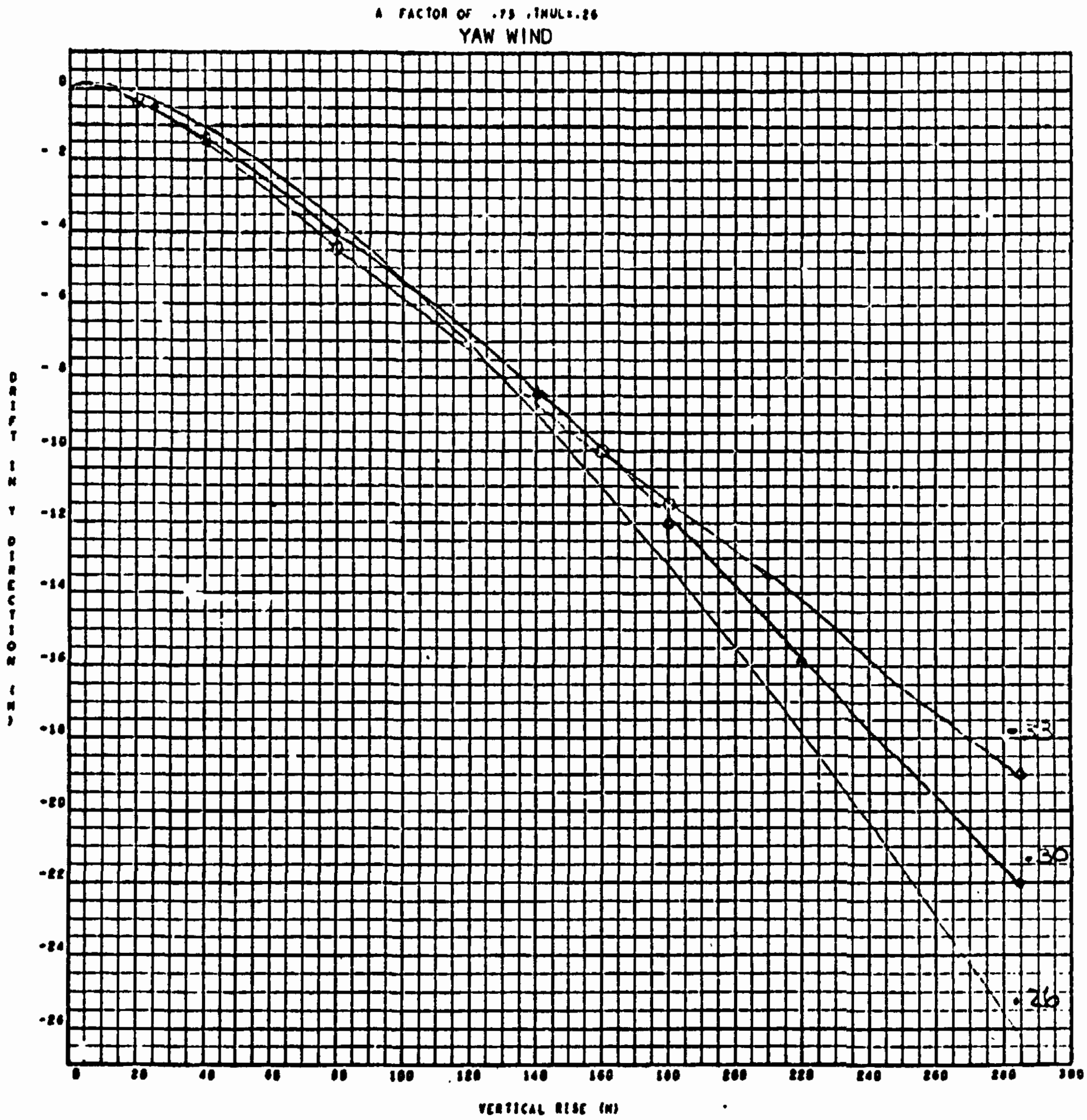


Figure 16. Lift-off RSS y drift comparison for 049.

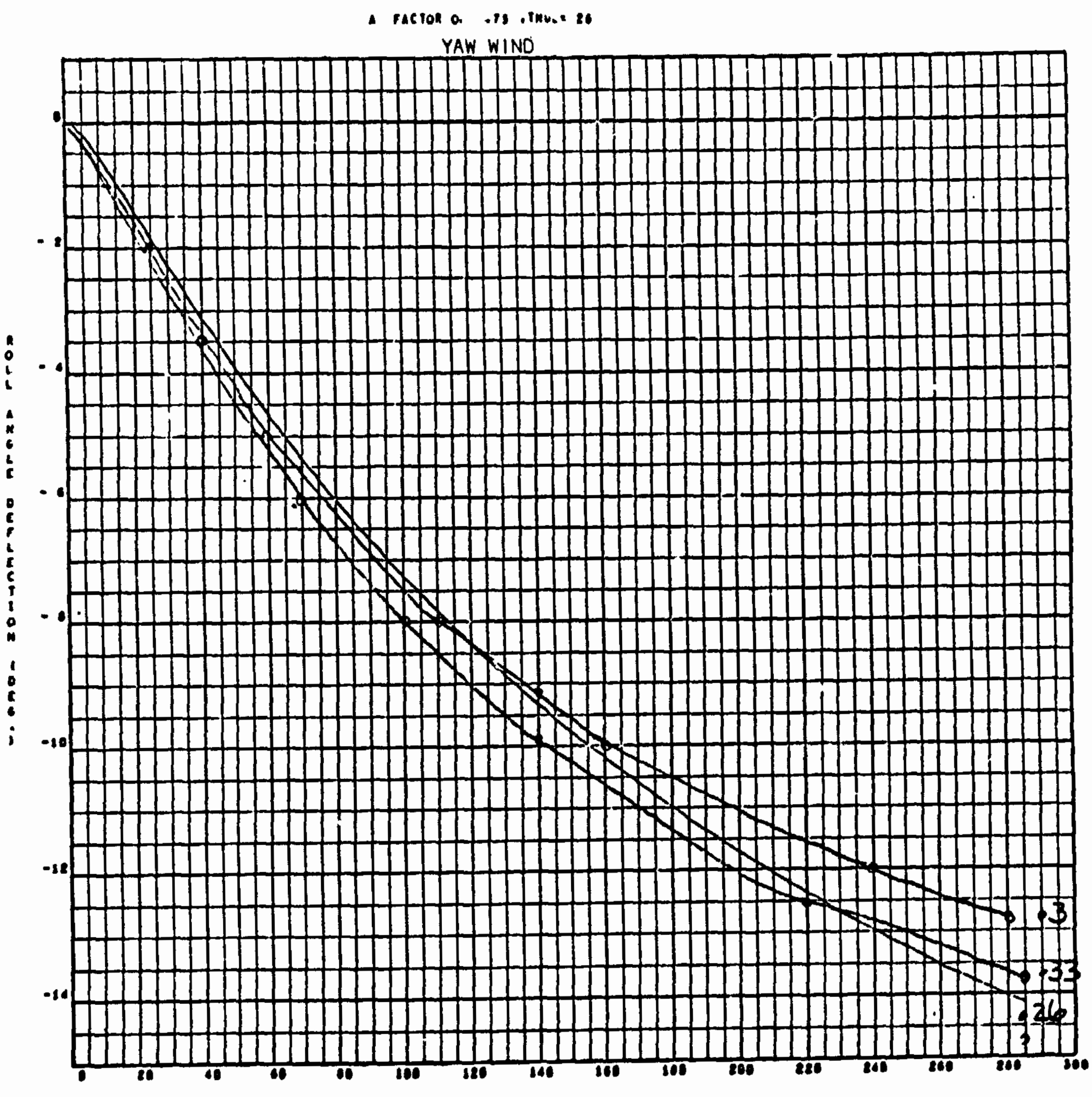


Figure 17. Lift-off RSS roll angle comparisons for 049.

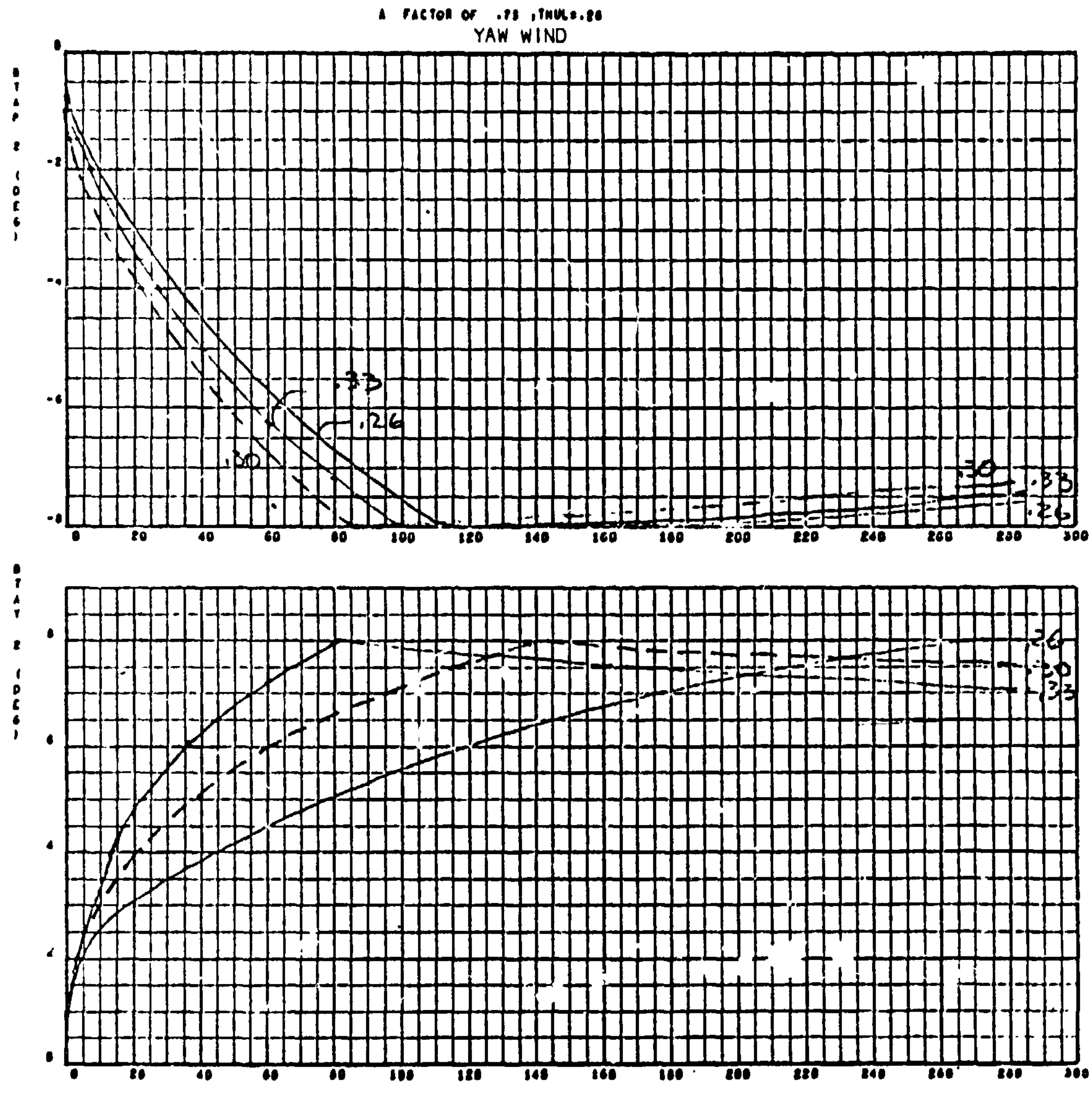


Figure 18. Lift-off RSS gimbal deflection comparisons for 049.

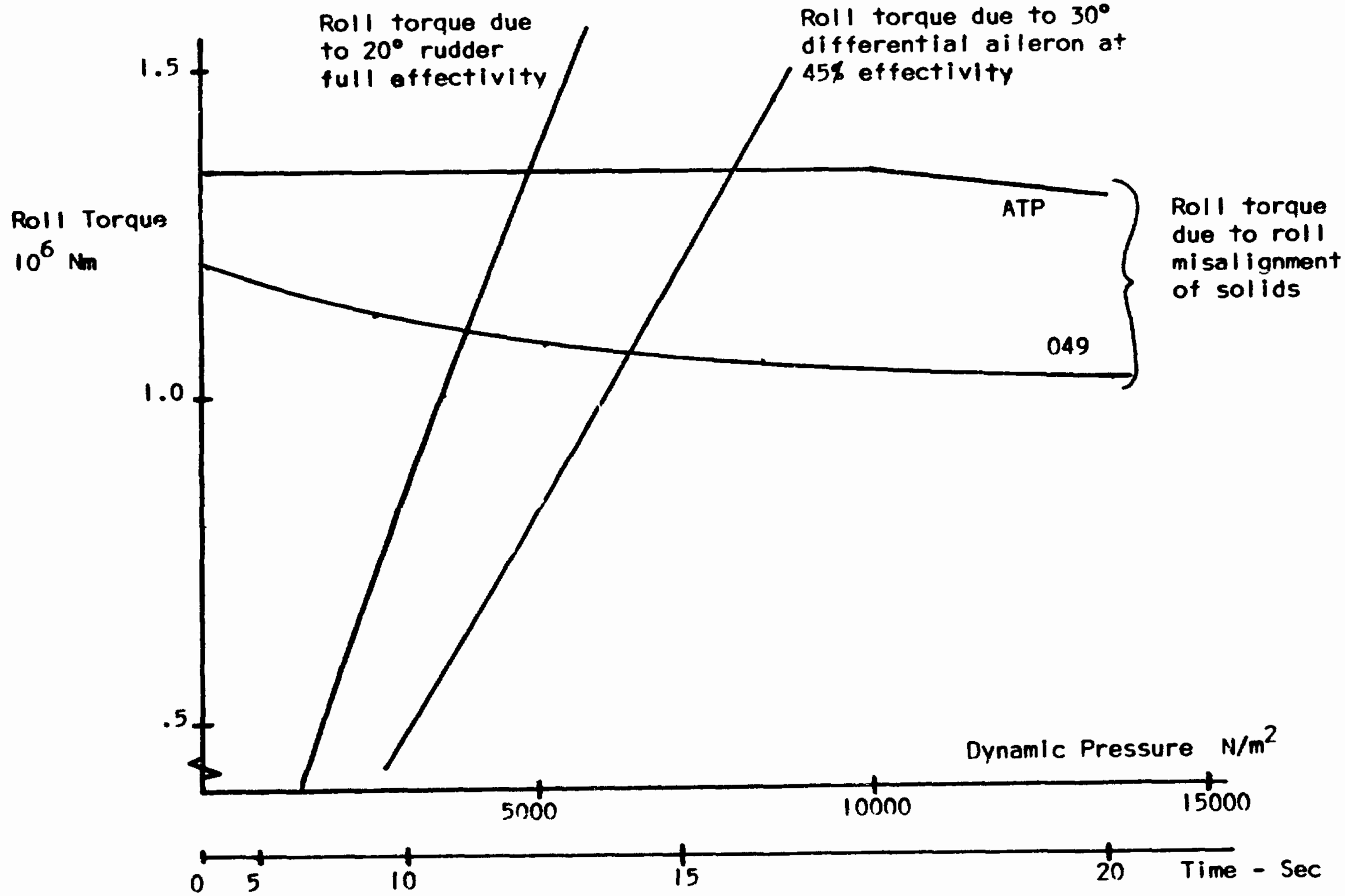


Figure 19. Aerodynamic control surface moment producing capabilities.

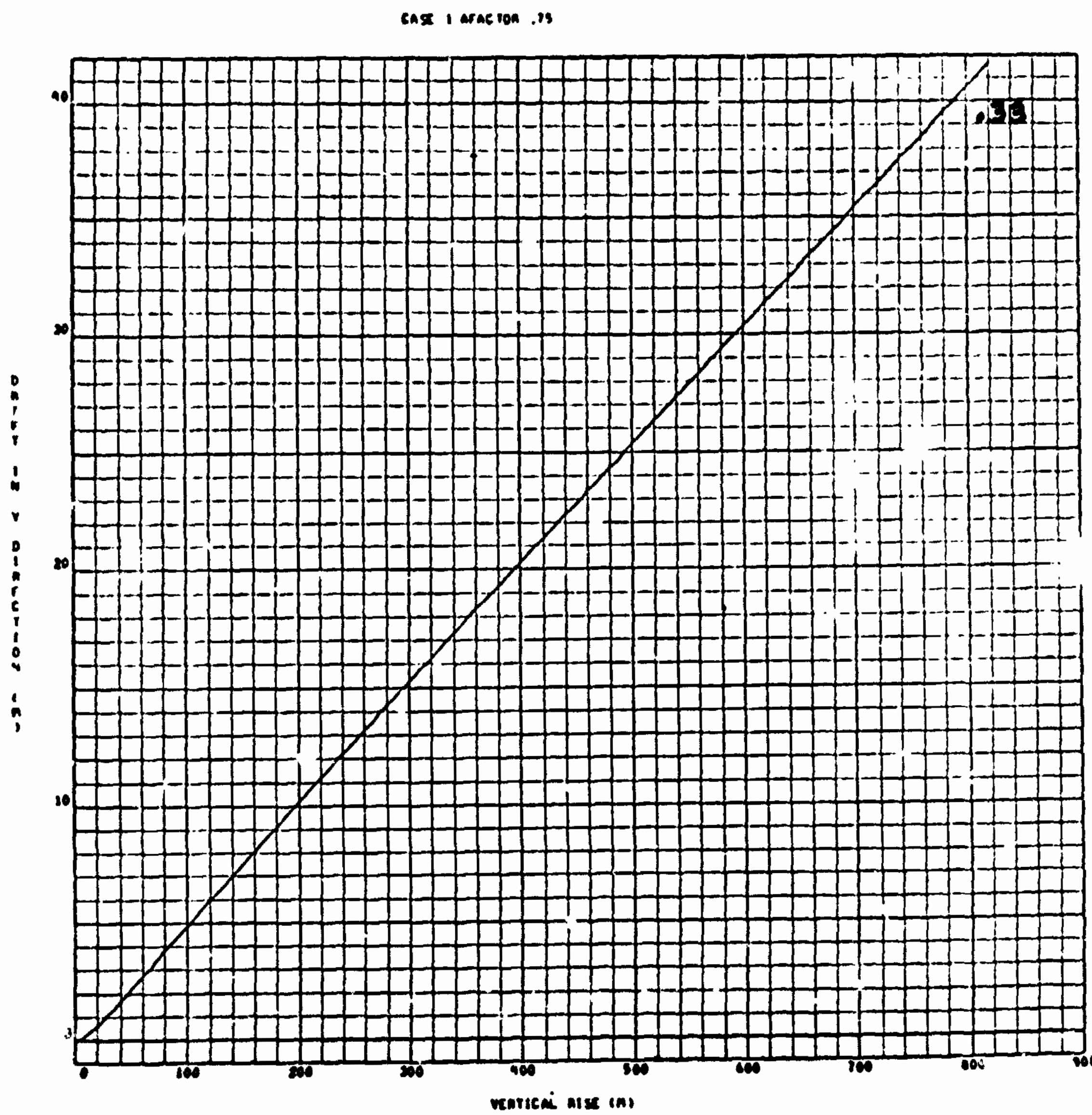


Figure 20. Lift-off RSS y drift comparisons for ATP configuration.

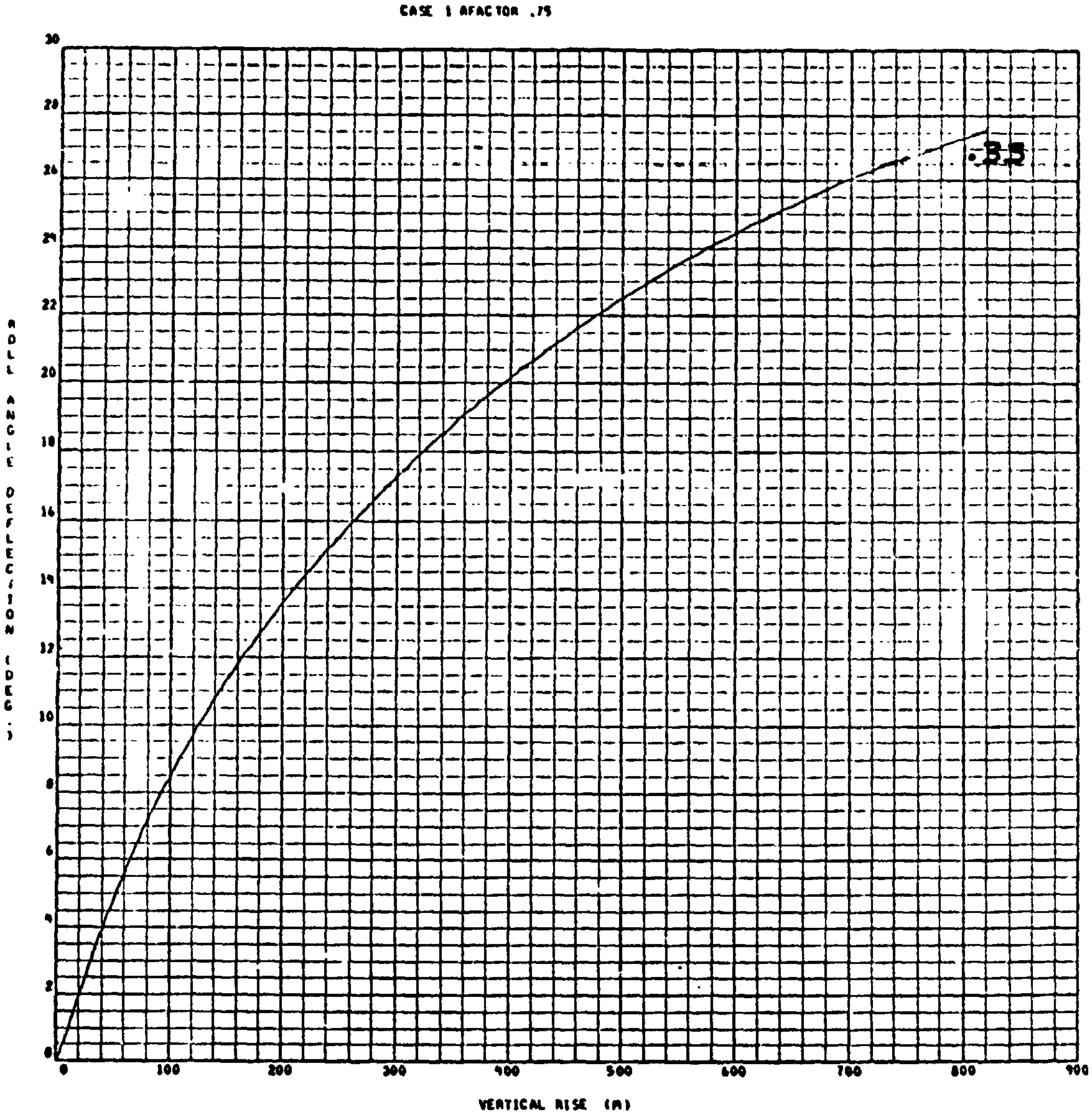


Figure 21. Lift-off RSS roll angle comparisons for ATP configuration.

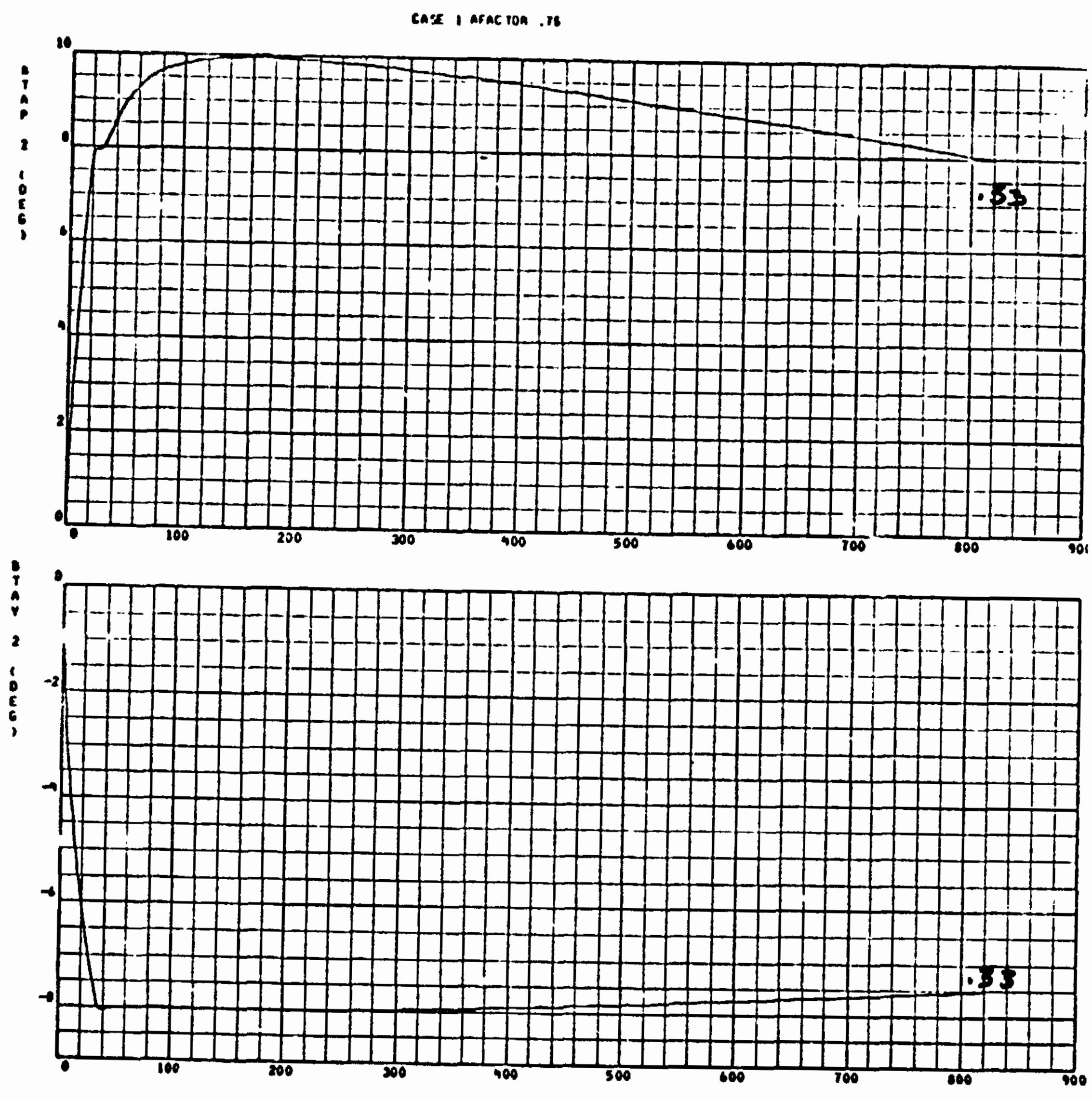


Figure 22. Lift-off RSS gimbal deflection comparisons for ATP configuration.

The effect on roll error, if the 35° roll command is instituted early (5 seconds), is shown on Figure 23. The lack of control authority to achieve this early roll maneuver led to delaying the maneuver until 15 seconds in order to have the aerosurfaces effective. This delay costs about 800 pounds injected weight.

In summary, lift-off is marginal from the controllability standpoint and could have a potential influence on trajectory shaping, particularly if an integrated lift-off, high q wind profile is used. These results will be presented later since this wind affects both lift-off and high q.

SRB TVC easily handles the lift-off problem with a 1° SRB thrust misalignment. Using a one degree per second rate limited system, the control requirements are near the misalignment values. Figure 24 is a typical time plot of one SRB engine during lift-off with the 1° thrust misalignment showing the capability of the system to control the vehicle during lift-off with large control margins, even with the large SRB thrust misalignments.

b. Thrust Tail-off. SRM's have the basic characteristics of fairly long thrust tail-offs and a large 3σ thrust delta between two corresponding motors during this time (Fig. 25). If the vehicle is flown without SRB TVC, this large thrust delta requires that the two individual motor's thrust be aimed through the c.g. or the result will be saturation of the orbiter main engine control requirements. Saturation of the control system would result in untenable separation conditions. Since this is a nonaerodynamic flight regime, only the main engines are available for control.

If SRB TVC is chosen, it is desirable to take advantage of the increased control moment produced by this approach by reducing the cant angles and picking up the large GLOW savings that result from the cosine loss. The amount of cant reduction is somewhat dependent upon the ability of the SRB TVC to handle the tail-off thrust deltas.

2. AERODYNAMIC REGIONS (HIGH q)

The solution to the high q control authority problem can take many forms due to the availability of aerosurfaces and the potential use of aerodynamic fins. Due to the simultaneous occurrence of high wind speed and high dynamic pressure, a threefold trade must be made between control authority requirements, performance losses, and structural loads. Since both vehicles studied have large aerodynamic stability, the natural tendency of the vehicle is to turn into the wind and reduce loads at the expense of trajectory dispersions (FPR losses). Any attempt to reduce this tendendy to turn into the wind increases both loads and control authority requirements.

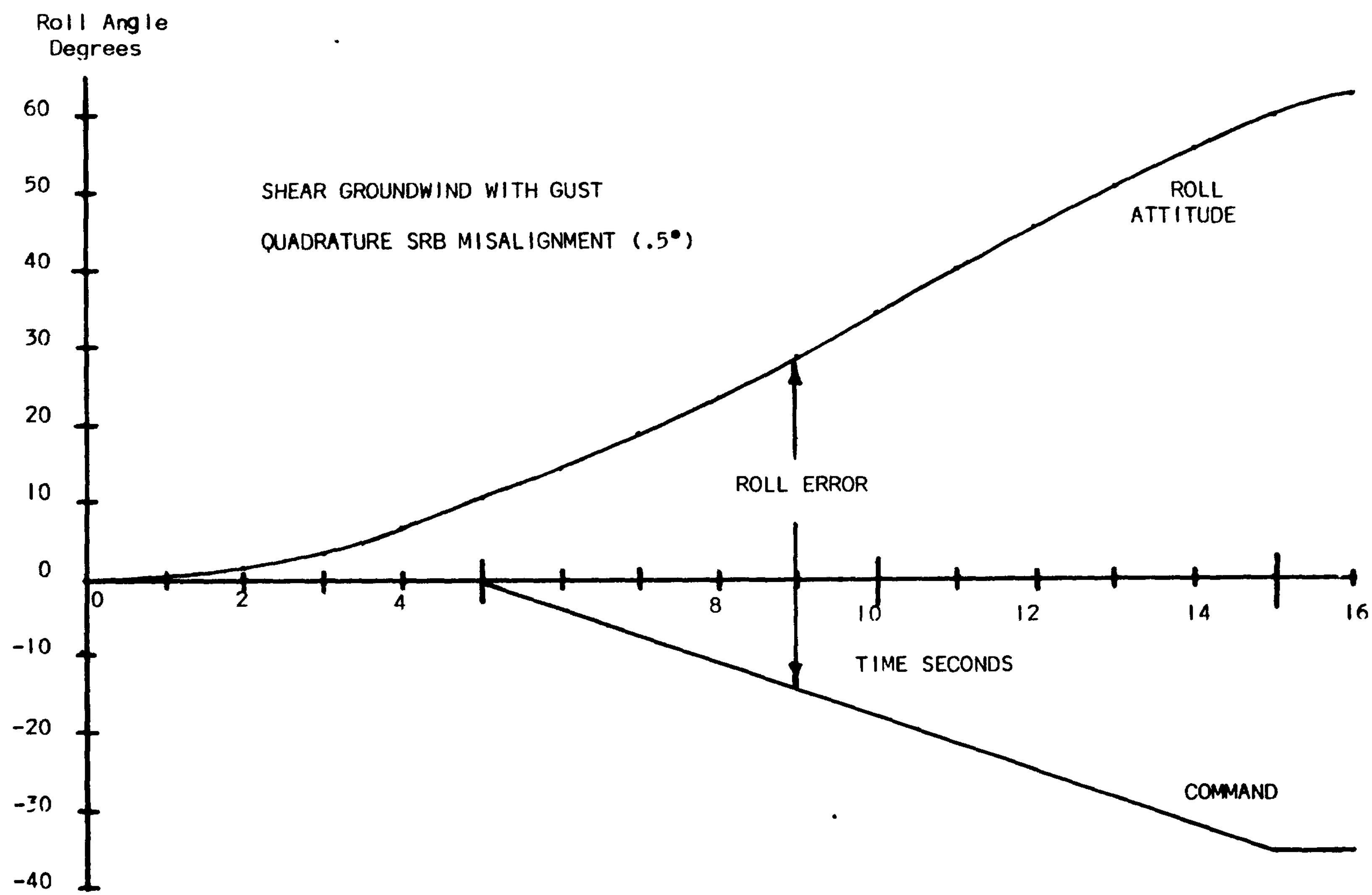


Figure 23. Roll response to commanded roll including influence of misalignments.

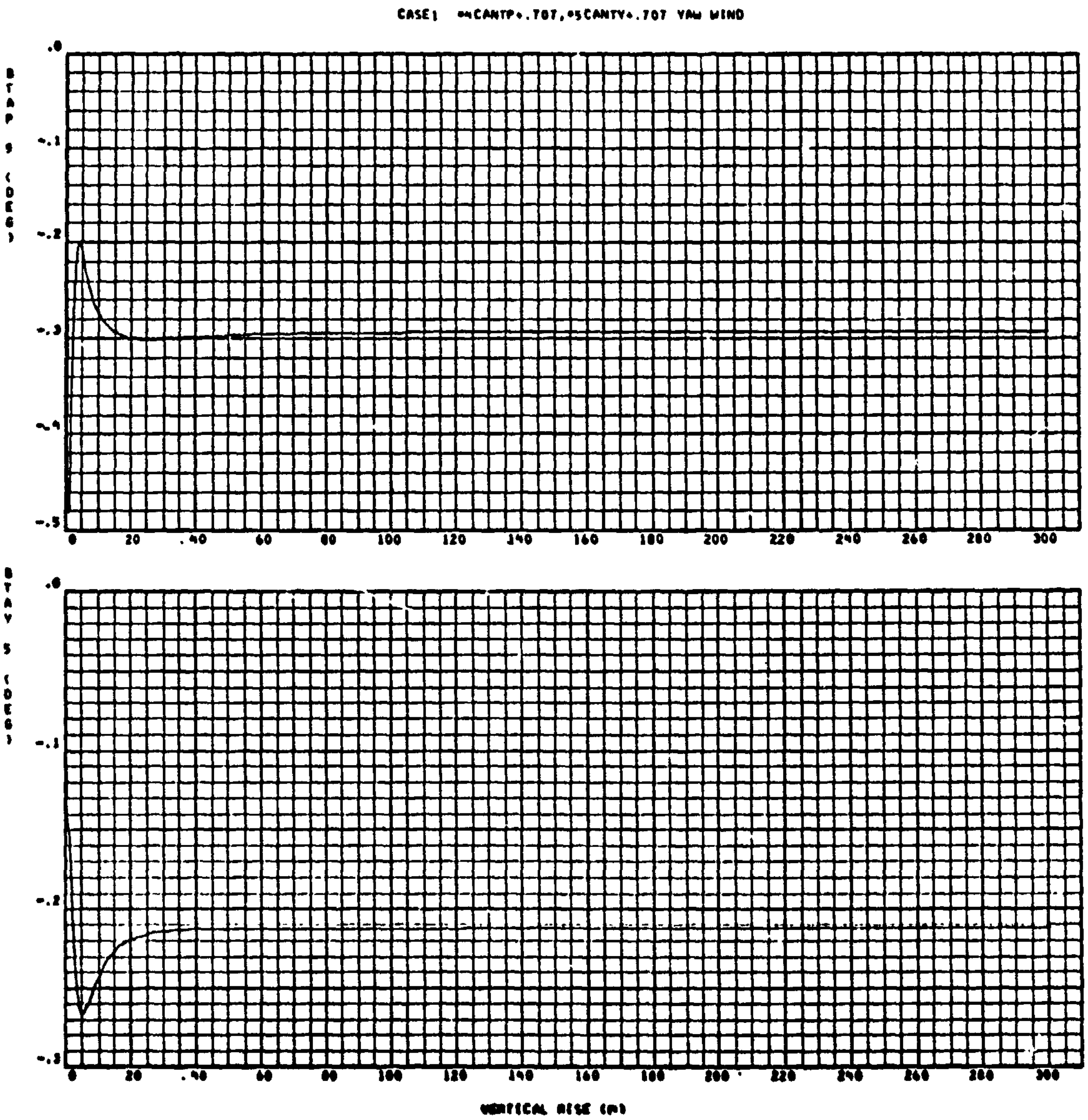


Figure 24. Time plot of one SRB engine during lift-off with 1° thrust misalignment.

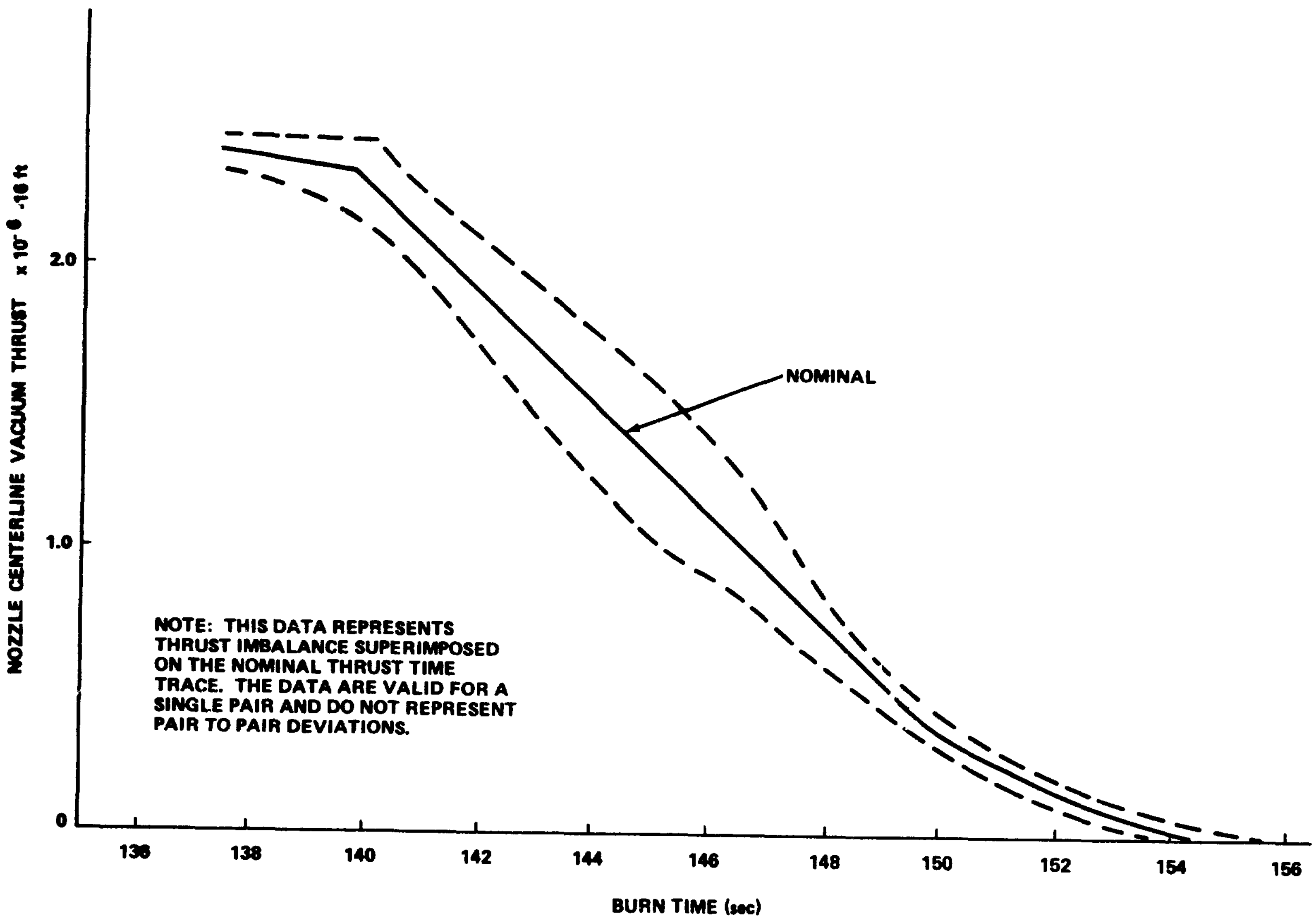


Figure 25. Predicted motor to motor nozzle centerline vacuum thrust tail-off envelope for a single pair of 156 inch diameter solid motors.

Fins can be used on both vehicles to accomplish the dual purpose of decreasing the yaw plane aerodynamic stability and the aerodynamic yaw-roll coupling. A detailed discussion of an optimized fin size and location trade study is in Section 7.

The ailerons are used primarily to augment roll control while the rudder can be used in either yaw or roll. Whether to feed back roll commands or yaw commands, or a mixture, to the rudder is a major question, since any rudder deflection creates both a yaw and roll moment. From the load standpoint, it is desirable to unload the rudder, reducing the yaw and roll moment for these vehicles. In the case of the 049 configuration, it was best to only feed roll commands to the rudder, while the large yaw plane aerodynamic stability characteristics of the ATP configuration necessitated feeding both yaw and roll commands to the rudder during high q.

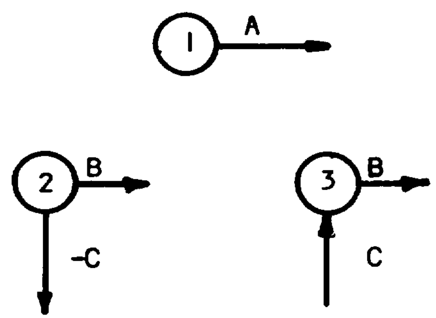
Control gains must be time programmed to handle the changing vehicle aerodynamics conditions and control authority requirements. This requires a blending between the lift-off control logic concept and the high q concept under discussion; the latter allows some vehicle weather cocking and use of aerodynamic surfaces. After dynamic pressure is reduced the control logic system must be blended back to the type used at lift-off. Individual time programmed gains to each actuator or a mixer approach is required to accomplish this (Fig. 26). The results presented in this section are based on the individual time programmed actuator gains. In section 4, a detailed discussion of the mixer (MOSES) approach with results is given. The appendix has the control gains used for each configuration.

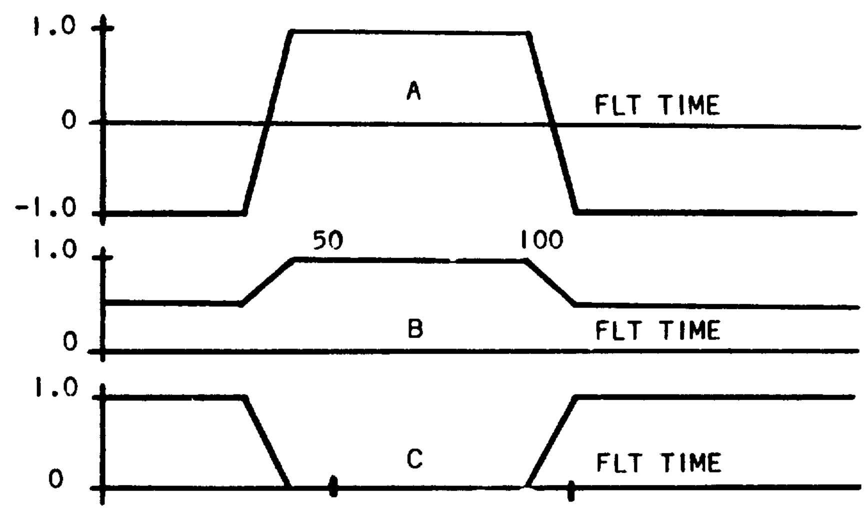
a. Pitch Plane. The effect of the electronic attitude command soft limit on pitch plane control is given on Figure 27 for the 049 configuration. This soft limit is used to allow control authority for stability consideration and was not working for the 8° soft limit case with the engines hitting the hard limits (mechanical) for about 2 seconds for a combined SRB thrust misalignment and winds. Reducing this soft limit to five degrees kept the engines from hitting the mechanical stops and provided the two degrees needed for stability. However, the reduced control authority available for path control led to approximately 6,000# loss of injected weight. Repeating the same case, using an 8° soft limit, gained 3,000# injected weight. The figure shows both head and tailwind cases for positive and negative thrust misalignment (cant change) with 5° and 8° soft limits on the attitude command. The sensitivity and marginality of the system are clearly demonstrated by these results and also show the fine tuning necessary to fly without SRB TVC. For this vehicle, loads were not a problem since all $q\alpha$'s were under 4000. The engine

OBJECTIVE: IMPLEMENT A PRACTICAL BLENDER THAT APPROACHES THE OPTIMUM SOLUTION BY CONSIDERING THE VARYING CHARACTERISTICS OF THE EFFECTORS AND VEHICLE WITH MACH NUMBER.
DEFINE A SLOW RATE SRM TVC SYSTEM.

SOLUTION CHARACTERISTICS:

ROLL LOGIC VARIATIONS
A, B, & C ARE ENGINE DEFLECTIONS
PER DEGREE ROLL COMMAND





VERIFICATION:
1. WIND GUST AT 3, 5, 7, 8, 9, 10, 12 KM
2. ALL SRM MISALIGNMENTS
3. MAJOR WIND DIRECTIONS (HEAD, TAIL, CROSS, QUARTERING)

Figure 26. Ascent control logic.

	$q\alpha$	δ_p	θ	Δ INJECTED WT. (35,9130#)
NOMINAL HEADWIND				
5° LIMIT	3832	-7.3	6.1	-640
8° LIMIT	3886	-9.0	3.8	-2610
NOMINAL TAILWIND				
5° LIMIT	1672	6.6	11.1	+730
8° LIMIT	2300	9.7	5.5	+2930
HEADWIND				
-.35° CANT				
5° LIMIT	3594	-6.6	3.1	-1030
8° LIMIT	3873	-7.6	3.8	-1500
+.35° CANT				
5° LIMIT	3480	-7.4	9.7	-240
8° LIMIT	3893	-10 (1.5)	3.9	-3000
TAILWIND				
-.35° CANT				
5° LIMIT	1400	7.0	19.6	-6600
8° LIMIT	2100	10.0 (1.0)	6.5	+2830
+.35° CANT				
5° LIMIT	1985	6.3	6.9	+2050
8° LIMIT	2300	9.1	5.0	+2720

Figure 27. Pitch plane SRM misalignment study.

deflection is indicated by $\hat{}_{p}$ and the attitude error at SRB separation by θ. The injected weight is deltad to 359,130 pounds. A comparison of the 8° soft limit case with and without SRB TVC is shown in Figure 28. With SRB TVC the $q\alpha$'s tended to increase, giving a slight gain in performance. Through a change in control logic, the loads could be reduced by increasing the performance loss.

Figure 29 is the same type analysis for the ATP vehicle and produces the same basic trends.

b. Yaw-Roll. To solve the yaw-roll problem for both the ATP and 049 configurations, a vertical fin had to be added at the ET intertank area. The 049 vehicle needed the fin to reduce both yaw stability and yaw induced rolling moment, while, for the ATP configuration, the main purpose was to reduce the yaw aerodynamic stability and reduce large performance losses. The 049 configuration required a 400 sq. ft. fin while the ATP vehicle needed nearly 600 sq. ft.

Figure 30 summarizes the 049 configuration results, with and without SRB TVC, for various SRB thrust misalignments and crosswinds. Only the rudder and orbiter main engines were used for control for the no SRB TVC case because of the large weight penalty incurred when using ailerons. Maximum engine deflections, roll and yaw attitude errors, load indicators ($q\beta$), and performance losses were acceptable for all cases.

The ATP vehicle had more problems, as indicated on Figures 31 and 32, particularly without fins. By using both ailerons and rudder with orbiter main engines, the engines were at the mechanical limits and performance losses were greater than 6000 pounds injected weight. With an 800 sq. ft. fin these performance losses dropped to 600 pounds or less, but the engines still hit the mechanical limit for one SRB misalignment (yaw plane). In both these cases, the rudder and aileron were used to their reentry hinge moment limit. Figure 33 is the case for the ATP vehicle using SRB TVC and indicates no basic problems. This was a one degree per second rate limited SRB TVC system.

The summary chart for the ATP vehicle is given in the Executive Summary and is not repeated here. This vehicle is very marginal from both the control and performance standpoints, requiring some major changes. This is true for both lift-off (Part 1, section 3) and high q, just presented.

		MAX VALUES NEAR 10 KM GUST				δ_P for TVC/SRM's BOTH SSME'S & SRM'S
		α DEG	δ_P DEG	$q\alpha$ PSF.DEG	Δ WT LBS.	
HEAD NOM	FIN	7.5	9.0	3890	-2610	
	TVC	8.3	-2.5	4250	-1630	$q\alpha$ PENALTY 1200 LBS.
TAIL NOM	FIN	-5.7	+9.7	2300	+2930	
	TVC	-7.7	+3.6	3180	+2460	
HEAD $+\Delta\gamma_P$	FIN	7.5	-10.0	3890	-3000	SSME'S LIM FOR 1.5 SEC.
	TVC	8.3	-2.9	4280	-2450	$q\alpha$ PENALTY 1300 LBS.
HEAD $-\Delta\gamma_P$	FIN	7.5	-7.6	3870	-1500	
	TVC	8.2	-1.7	4120	-1480	
TAIL $+\Delta\gamma_P$	FIN	-5.8	+9.1	2300	+2720	
	TVC	-7.7	2.8	3155	+2150	
TAIL $-\Delta\gamma_P$	FIN	-5.2	+10.0	2100	+2830	SSME'S LIM FOR 1.0 SEC.
	TVC	-7.8	3.9	3195	+3320	

FIN $\Delta\delta_P$ .5 DEG TVC $\Delta\delta_P$ 1 DEG SRM MISALIGNMENTS

Figure 28. Pitch plane summary — comparison of 8° soft limit case with and without SRB TVC for 049.

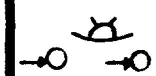
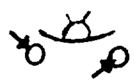
PITCH PLANE WIND RESPONSE SUMMARY NAR ATP

BASELINE SRB TVC

45 M/SEC WIND

		ι	$q\alpha$	δ_D	Δ Wt. INJ
6 Km HEADWIND	BASELINE 15° RUD, 30° DIF. AIL.	3.6	2590	3.5	-1200
	SRM TVC	3.6	2592	2.4	- 300
	BASELINE ↑↑ .3535°	4.0	2760	5.0	-1850
	SRM TVC ↑↑ .707°	5.6	4030	2.8	- 900
6 Km TAILWIND	BASELINE 15° RUD, 30° DIF. AIL.	-7.6	4110	10	-1360
	SRM TVC	-9.0	5010	515	+ 200
	BASELINE ↑↑ .3535°	-11.0	3650	10.0	-3600
	SRM TVC ↑↑ .707°	-6.6	3780	4.7	- 100

Figure 29. Pitch plane summary — comparison of 8° soft limit case with and without SRB TVC for ATP.

		β DEG	$q\beta$ PSF.DEG	SSME'S δ_P/δ_Y DEG	SRM'S δ_P/δ_Y DEG	Φ/Ψ DEG	$q\beta$ PENALTY LBS.	Δ WT LBS.	
NOMINAL	FIN	8.2	4020	2.0/3.2		4/3	200	-250	
	TVC*	8.4	4050	4.0/2.2	4.4/3.0	11/6	210	-300	
	FIN	9.7	4740	8.4/8.4		8/4	500	-700	
	TVC*	9.0	4500	5.0/3.0	5.0/2.0	15/7	400	-300	#4 LIM 10 SEC
	FIN	8.7	4310	8.0/8.0		8/3	330	-500	
	TVC*	9.0	4400	5.0/3.0	5.0/2.0	15/6	360	-900	#4 LIM 6 SEC
	FIN	9.7	4600	8.0/8.0		12/4	440	-500	
	TVC*	9.0	4300	5.0/3.0	5.0/2.0	15/7	330	-300	#4 LIM 10 SEC

NOMINAL RUDDER HINGE MOMENT LIMIT 10 DEG NEAR q MAX
FOR FIN CASE. *NO RUDDER USED FOR TVC/SRM CASES.

FIN .5 DEG TVC 1.0 DEG SRM MISALIGNMENTS

Figure 30. Yaw/roll summary for 049.

	$q\beta$	δ_p	δ_y	δ_{RUD}	δ_{AIL}	ΔWT_{INJ}
NOMINAL	2990	8	8.5			-1500
→ → .354°	2960	9	10	LIM	LIM	-6000^{+}
↓ ↑ .354°	3860	9	10	LIM	LIM	-6000^{+}
± 3.5% ΔF	3970	8	10	LIM	LIM	-6000^{+}
2 INCH Δ YCG	4510	8	10	LIM	LIM	-6000^{+}

Figure 31. Yaw plane wind response summary — 6 km crosswind — baseline vehicle.

	$q\beta$	δ_p	δ_y	δ_{RUD}	δ_{AIL}	ΔWT_{INJ}*
NOMINAL	3550	4.0	8.0			-170
.354° → →	4600	9.0	10.0	LIM	LIM	-650
↓ ↑ .354°	3760	8.0	9.0	LIM	LIM	-210
± 3.5% ΔF	4180	4.0	9.5			-360

* WEIGHT IMPACT OF FIN NOT INCLUDED.

Figure 32. Yaw plane wind response summary — 6 km crosswind — 800 sq. ft. fin at intertank.

	qβ PSF DEG	δ_p Solids	δ_y Solids	δ_p Liquids	δ_y Liquids	INJ* ΔWT lbs.	STR
NOMINAL	3550	2.6	1.8	3.0	5.0	-1180	-
→ →.707°	5400	3.5	3.0	3.5	7.5	-3400	100
↓ ↑ .707°	4800	3.5	2.0	2.5	5.0	-1370	-

* WEIGHT IMPACT OF TVC SYSTEM NOT INCLUDED.

Figure 33. Yaw plane wind response summary — 6 km crosswind — SRB TVC vehicle.

The 049 configuration was also analyzed for other potential high q solution options. Figure 34 shows the comparison for these additional options in terms of loads, control authority, performance loss, GLOW, and cost. Increasing the main engine gimbal capability to 13° did not increase vehicle performance, and engines were on the mechanical limit for 30 seconds and a roll rate of 13 deg/sec occurred. Increasing the rudder hinge moment by a factor of 2 produced a marginal system, but at an increased GLOW cost of 172,000 pounds and $70(M) total program cost. The 400 sq. ft. fin was acceptable from control authority and performance standpoint, but had a GLOW increase of 6080 pounds and a program cost of $50(M). The free roll case was marginal, with a GLOW increase of 133,000# required to make up performance losses and a total program impact of $76(M). The control engines still hit the mechanical limits. The SRB TVC saved 150,000# GLOW

	$q\alpha$ PSF DEG	$q\beta$ PSF DEG	CONTROLLABILITY	PERFORMANCE LOSS LBS	Δ WEIGHT LBS	Δ GLOW LBS	COST
BASELINE	4840	4840	ALL ENGINES ON STOPS $\dot{\phi} > 15°/SEC$	1800	3100	+111,000	
INCREASED SSME LIMITS	4177	3800	ALL ENGINES ON STOPS $\dot{\phi} > 13°/SEC$	2200	2000	70,000	
INCREASED RUDDER HINGE MOMENTS	5223	4300	MARGINAL	400	3500	+122,000	70,400,000
400 SQ FT VENTRAL FIN ADDED FORWARD	2020	4400	GOOD	710	1680# 1880#	6080#	35,000,000 15,000,000 50,000,000
FREE ROLL	6200	2700	MARGINAL	2000	3800	+133,000	76,120,000
1°/SEC SRM TVC 6° SRM CANT	2400	4500	GOOD	0	10,000#	-150,000	70,000,000 20,000,000 90,000,000
						TRIM	68,000,000

Figure 34. Summary – worst side wind (60 m/sec) and SRM tolerance.

for this vehicle at a program cost of \$70(M). The larger GLOW savings for SRB TVC for the 049 configuration over the ATP configuration that was presented in the Executive Summary is due to the larger cant (15°) that is required to track burnout c.g. for the 049 configuration. In summary, only three options appear feasible to solve the high q problem: (1) using orbiter aero surfaces, (2) using ventral fin, and (3) using an SRB TVC system. Only the SRB TVC system increases the control authority margin and effectively handles the lift-off and burnout flight regimes simultaneously. There is a potential loads problem with SRB TVC; however, this can be handled with proper control logic and some performance loss.

3. ELASTIC BODY EFFECTS

The stabilization of the elastic body modes, using orbiter only for control, is a very critical problem. This is because the launch system is basically four elastic bodies, spring connected at two points. To illustrate the problem of stabilizing the attached bodies, ET and SRB's, a two body problem was formulated by considering them to be rigid but connected by springs. In the analysis, the control sensor and control force could be located on the same body or on separate bodies. Figure 35 is a root locus for the case where the sensor and control force are on the same body and show that no damping can be added to the mode associated with the body that does not have the control force and control sensor[6]. Putting the sensor on one body and the control force on the other can help or hurt damping. The unstable case is shown on Figure 36. Sensors on each body improved the situation; however, for adequate stability, a control force and control sensor were required for each body.

General Dynamics Corporation conducted a full stability analysis for a parallel burn vehicle using three dimensional modes and found that, without nonconventional control or a full SRB TVC, adequate stability was not achievable. Root locus plots indicated these stability problems for orbiter only control for one rate gyro location and are shown on Figures 37 and 38.

The conclusion is evident that modal stability for this vehicle will be a real problem and one on which the proposed slow rate SRB TVC system will have no bearing, since it will not be able to respond to the modal frequencies. This forces three independent considerations: (1) make the SRB TVC a full rate system to remove the risk of modal instability, (2) conduct detailed elastic body modal characteristics analysis and test verification, and (3) make a study of nonconventional control system techniques.

6. Alberta W. King, Effect of Coupling Between Rotation and Bending Modes on the Stability of a Space Vehicle. MTP-AERO-63-77, November 1963.

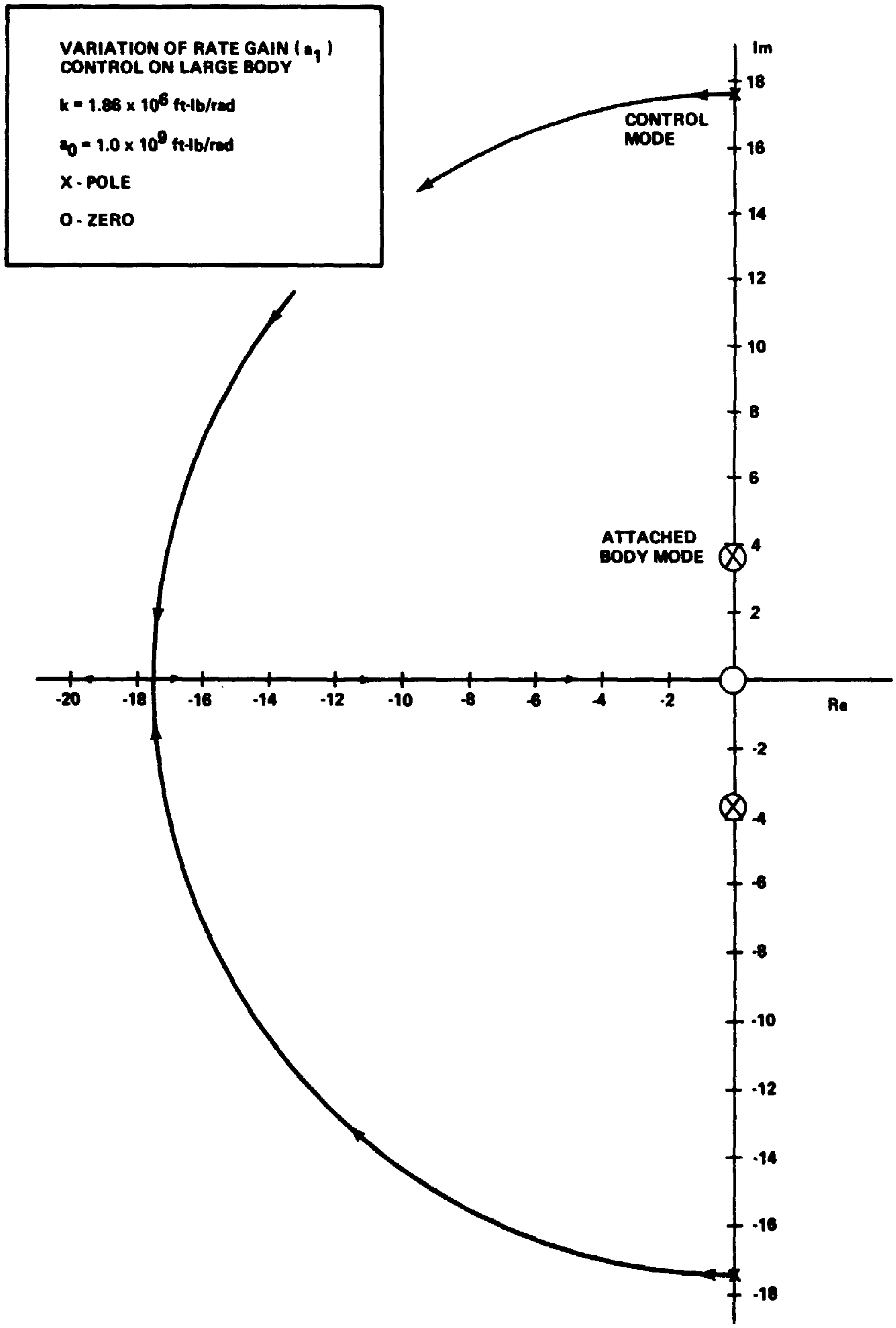


Figure 35. Root locus for spring connected bodies, control force, and sensors on the same body.

CONTROL GAINS INCREASING

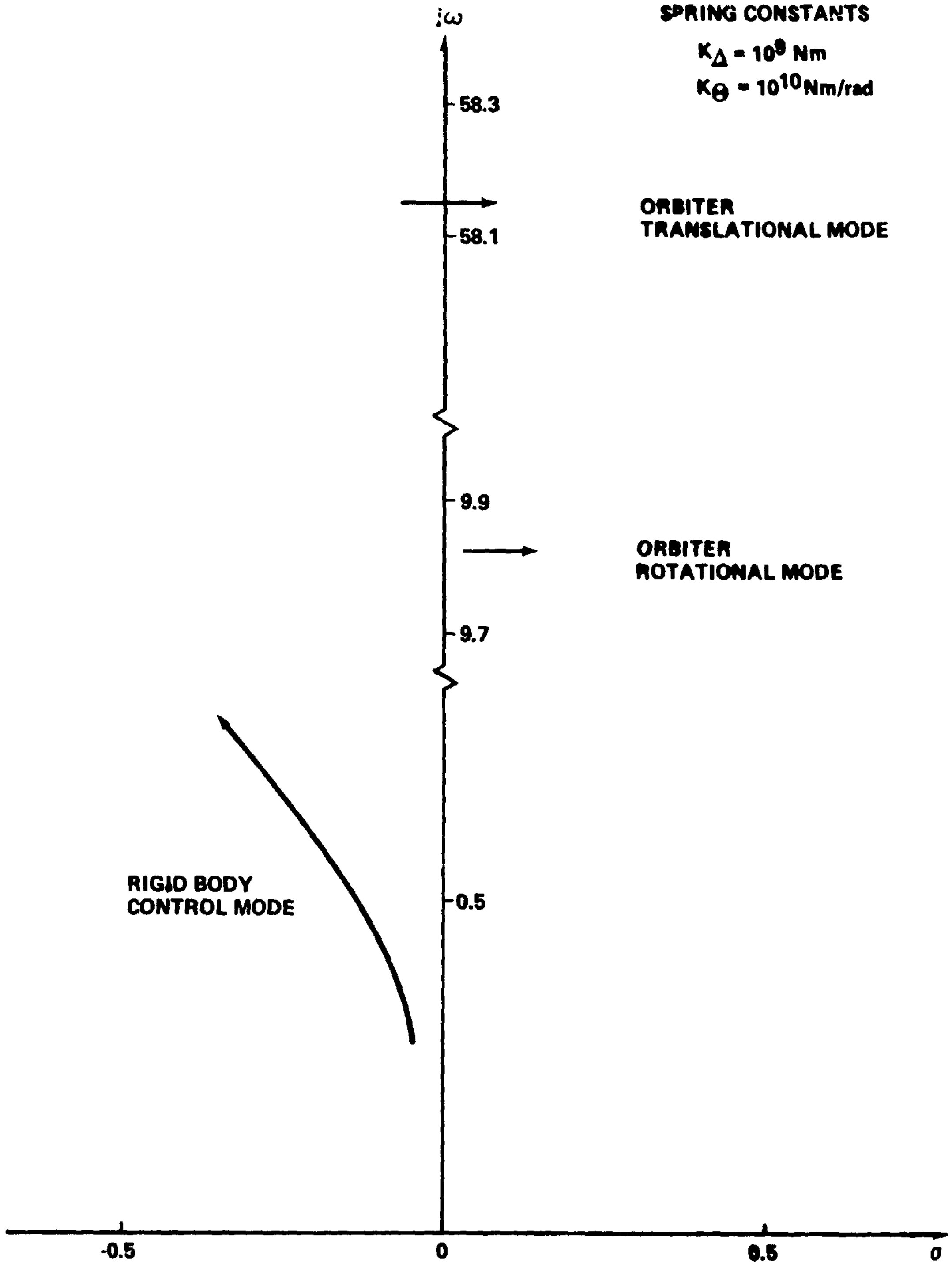


Figure 36. Root locus for spring connected bodies, control forces, and sensors on different bodies.

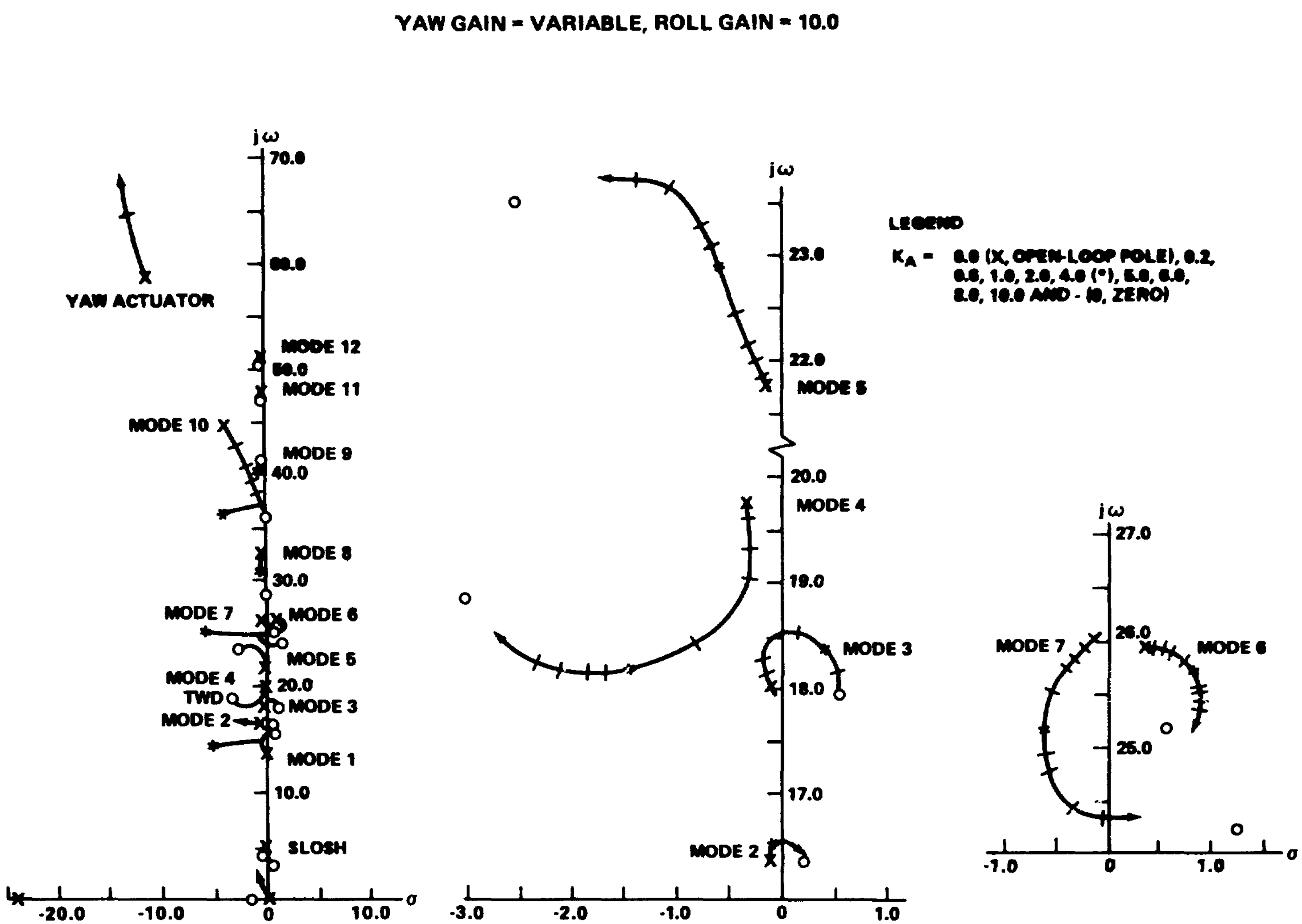


Figure 37. Coupled yaw/roll, aft rate sensors on orbiter.

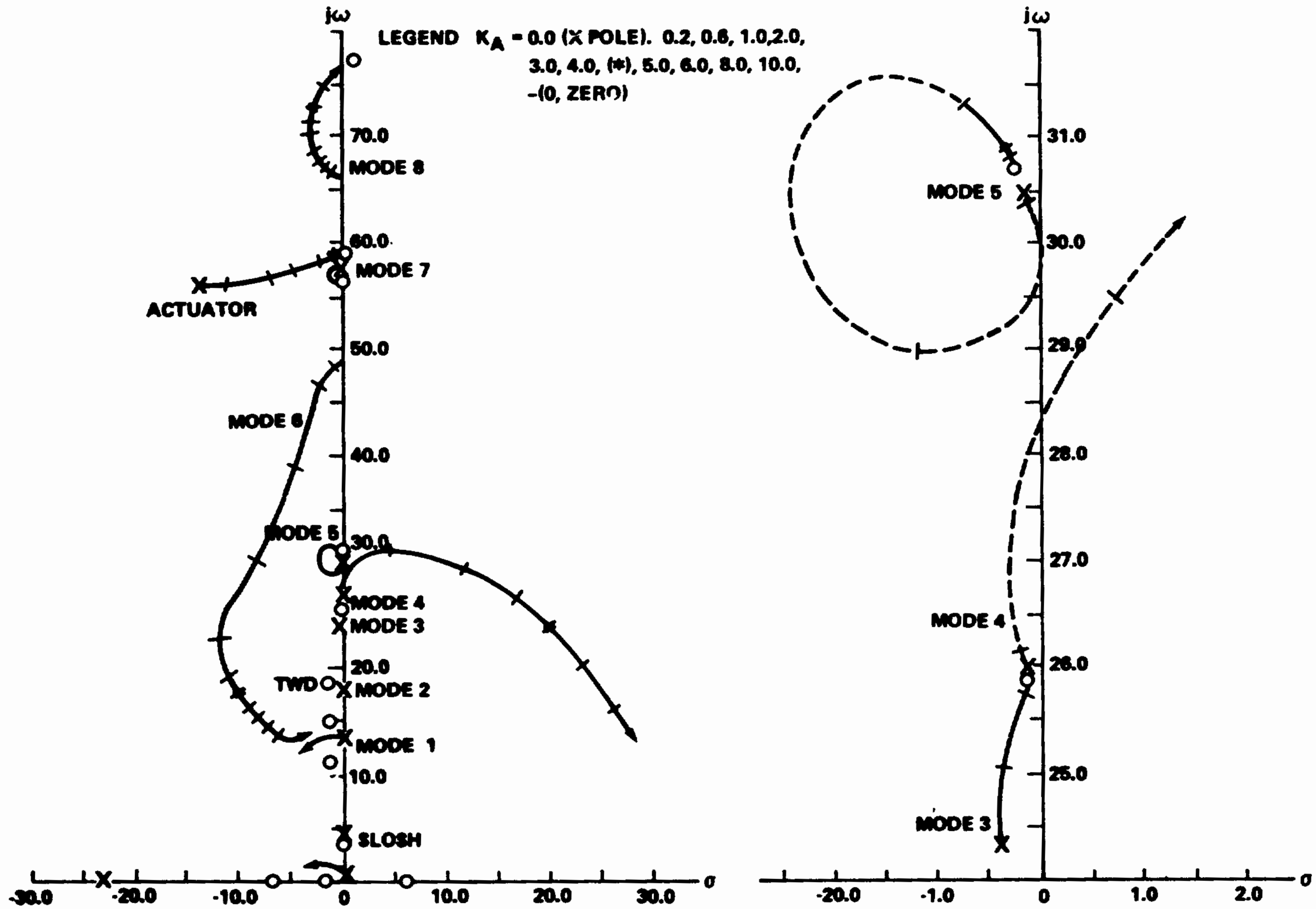


Figure 38. Coupled yaw/roll, forward rate sensors on orbiter.

4. MIXER CONCEPTS

One of the more significant control problems of these configurations is characterized by high yaw plane stability, complemented by roll-yaw coupling, which is caused by both the aerodynamics and the geometry of control. That is, an angle of sideslip, β, or a control deflection, δ , produces yaw and roll moments simultaneously. This can be graphically illustrated by the moment diagram for a given time point of the 049 configuration, as shown on Figure 39. A disturbing moment vector due to sideslip (shown per degree on the figure), or due to SRM misalignments, must be offset by the resultant of the control effector vectors for vehicle trim. To achieve simultaneously zeroed (trimmed) roll and yaw moments, the effector magnitudes must be manipulated so that their resultant is collinear with and of the same magnitude as the disturbance vector. Obviously, to accomplish this, a number of choices may exist, with the number increasing for a larger number of control effectors.

The specific choice of how to blend, or mix, the various control effectors to produce control torques collinear to the disturbances has significant effects on the ability of the vehicle to control within the prescribed position limits placed on the individual effectors. Two approaches were taken to implement a blender. First, the flight regime was separated into the two regions: aerodynamic and nonaerodynamic, which gave three trajectory areas — lift-off, high q, and tail-off. An average optimum mix was achieved for each region of the 049 configuration flight and the mixing gains were ramped from one trajectory area to the other around 40 seconds and 100 seconds of flight time (see Figure 26). The second method minimized a weighted quadratic performance index of effector deflections to supply the additional constraints that are needed to produce two moments (yaw and roll) with four or more control effectors[2]. The relation of this complete timewise optimum approach to the rest of the vehicle system is shown on Figure 40. This mixer uncouples the control laws from the effectors and achieves a more easily understandable system, while the first approach only accomplishes it for the average vehicle characteristics. Both methods have been given the acronym " MOSES."

The second type of blending is particularly adaptable to the coupling problems of the Shuttle configuration. This configuration utilizes a number of control effectors which, when deflected, produce moments about more than one axis. These configurations control with engines gimballing in pitch and yaw, with rudders, and possibly, on the ATP configuration, with ailerons. Differences in the basic aerodynamics of the two configurations (the ATP is

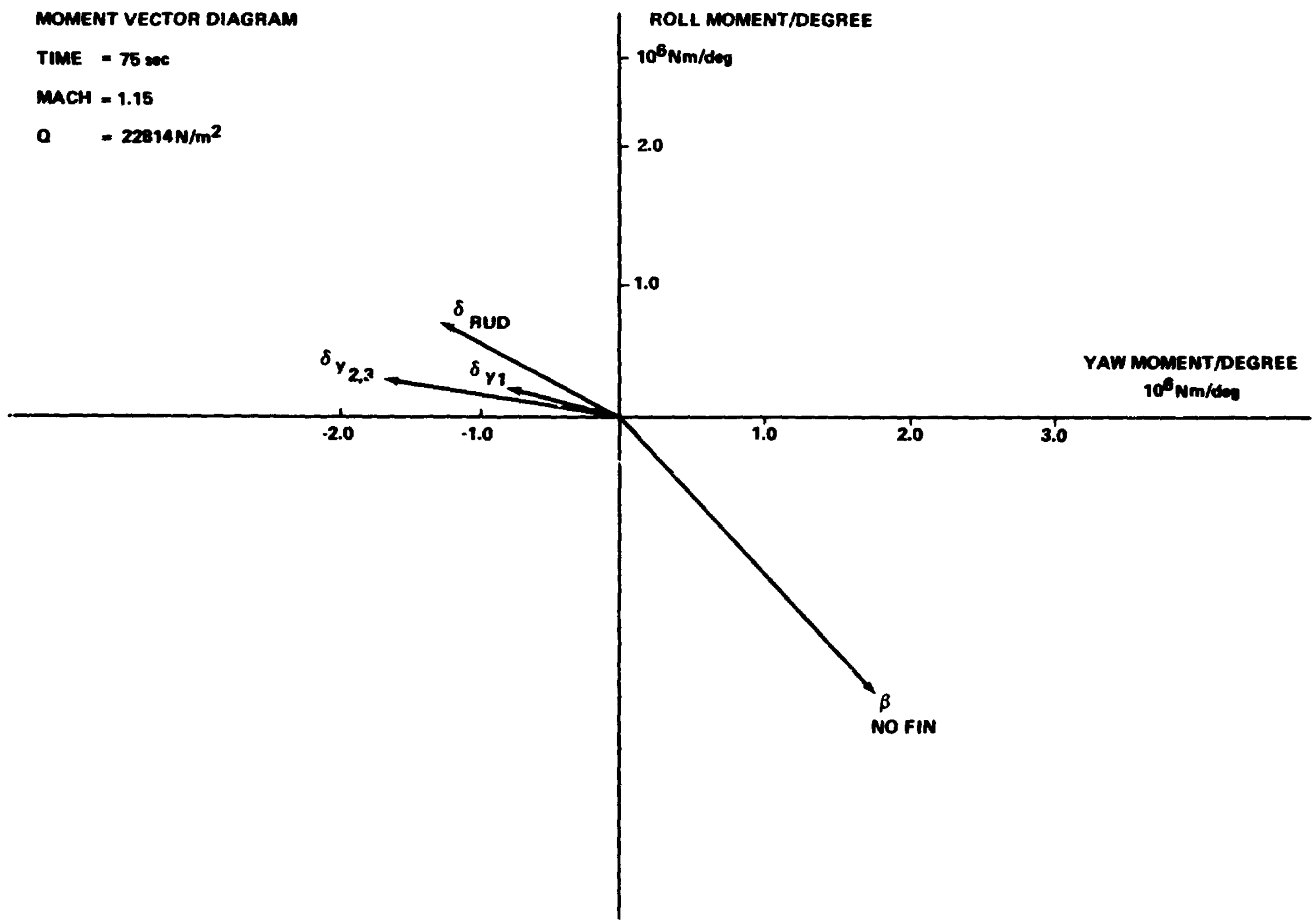


Figure 39. Moment vector diagram for 049.

PROBLEMS:

(1) DISTURBANCE MOMENTS AND CONTROL MOMENTS ARE NOT COLLINEAR.

(2) MARGINAL CONTROL MOMENTS MAGNITUDE RELATIVE TO DISTURBANCE MOMENT MAGNITUDE (SRM TOLERANCES, WINDS).

(3) EACH CONTROL EFFECTOR HAS DIFFERENT YAW-ROLL COUPLING CHARACTERISTICS.

OBJECTIVE: SEPARATE THE MIXING LOGIC FOR THE CONTROL EFFECTOR CHARACTERISTICS FROM THE NORMAL CONTROL LAWS FOR RESPONSE CHARACTERISTICS TO ACHIEVE SIMPLICITY OF OPERATIONS AND UNDERSTANDING.

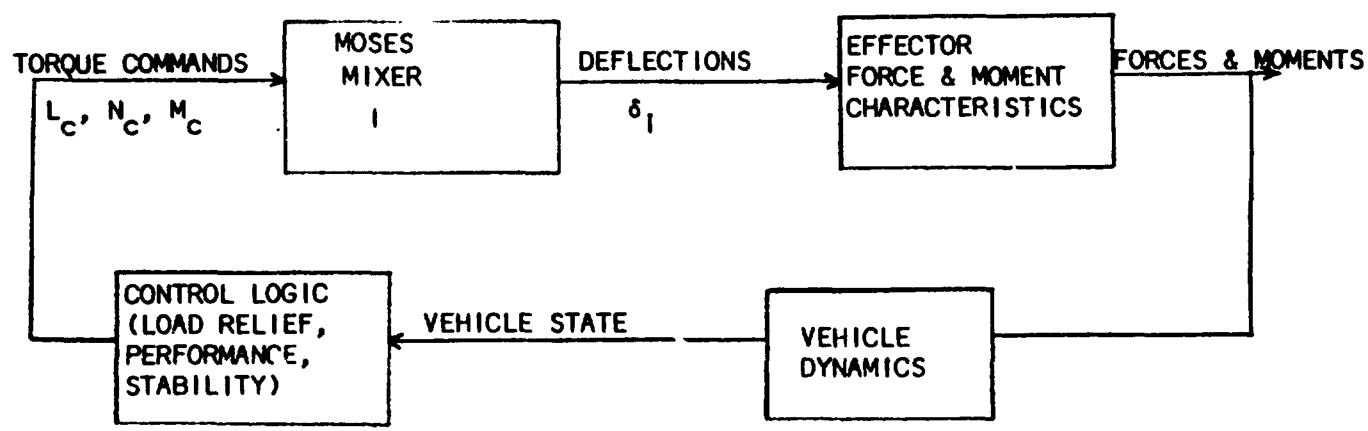


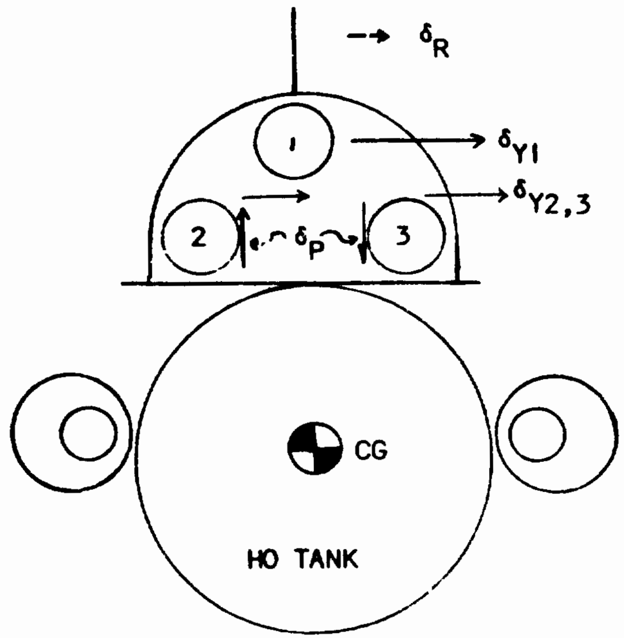
Figure 40. MOSES mixer concept.

considerably more stable in yaw than the 049 configuration) will cause some changes in the control laws between the vehicles, but the MOSES techniques present an optimum and consistent method of producing the desired control torques from the available effectors once the command level of control torque is determined by the control laws. The studies reported herein include only the roll and yaw moment generation, but extension of the techniques for pitch moment generation is obvious.

Additional details of the MOSES mixer are included on Figure 41. The weighting matrix essentially contains the square of the deflection limits for each of the effectors as the main diagonal terms but correlation effects can be used if desired. In the case of the aerodynamic surfaces, the limits may vary with dynamic pressure. The use of partials, of course, implies linearization about an equilibrium point.

a. Weighting Effects on Control Authority. Weighting effects are illustrated by comparison of Figures 42 and 43. These figures present the amplitudes of the individual effectors (δ_{y1}, δ_{y2}, δ_R and δ_P), as commanded by the MOSES mixer in static analysis at maximum dynamic pressure with an assumed 10° sideslip angle for an 049 configuration with a 400 sq. ft. ventral fin. Several cases are included. Case 1 is for the nominal vehicle; the other cases, 2 through 9, have different SRM misalignments, as well as the 10-degree sideslip disturbance. Weightings from Figure 42 essentially say that all effectors can be used to 10° without excessive weighting penalties, but Figure 43 weightings only allow 5° for rudder and pitch engine deflection before weighting penalties become large. Comparison of the two figures shows that, at this maximum q region, the rudder is quite effective and the mixer uses it to keep the engine 1 yaw deflection (δ_{y1}) reduced. When the allowable rudder is reduced, however, large yaw deflection from engine 1 (δ_{y1}) is now required to make up the remaining moment, and its commanded deflection exceeds the ten degree limits.

b. Effect of Correlation Factors on Control Activity. Some correlating effects are shown on Figure 44, where effector deflection per degree of sideslip is plotted versus correlation factor for differential pitch deflection (δ_P) correlating with engine 1 yaw deflection (δ_{y1}) and for rudder deflection (δ_R) correlating with engine 2 yaw deflection (δ_{y2}). Because of the high slopes for large values of correlation for the latter case, it becomes obvious that minimum correlation should be maintained between rudder deflection and engine 2 yaw deflection for this flight condition.



L_i weighting values
ρ_{ij} interaction coefficients
F side force
L roll moment
N yaw moment
δ_p differential deflection in pitch

$$T = WC^{\dagger}(C\,W\,C^{\dagger})^{-1}$$

WEIGHT MATRIX

$$W = \begin{bmatrix} L_1^2 & \rho_{12}\,L_1L_2 & \rho_{13}\,L_1L_3 & \rho_{14}\,L_1L_4 \\ \rho_{21}\,L_2L_1 & L_2^2 & \rho_{23}\,L_2L_3 & \rho_{24}\,L_2L_4 \\ \rho_{31}\,L_3L_1 & \rho_{32}\,L_3L_2 & L_3^2 & \rho_{34}\,L_3L_4 \\ \rho_{41}\,L_4L_1 & \rho_{42}\,L_4L_2 & \rho_{43}\,L_4L_3 & L_4^2 \end{bmatrix}$$

EFFECTOR CHARACTERISTICS

$$C = \begin{bmatrix} \frac{\partial L}{\partial \delta_1} & \frac{\partial N}{\partial \delta_1} & \frac{\partial F}{\partial \delta_1} \\ \frac{\partial L}{\partial \delta_2} & \frac{\partial N}{\partial \delta_2} & \frac{\partial F}{\partial \delta_2} \\ \frac{\partial L}{\partial \delta_R} & \frac{\partial N}{\partial \delta_R} & \frac{\partial F}{\partial \delta_R} \\ \frac{\partial L}{\partial \delta_P} & \frac{\partial N}{\partial \delta_P} & \frac{\partial F}{\partial \delta_P} \end{bmatrix}$$

Figure 41. MOSES current mixer.

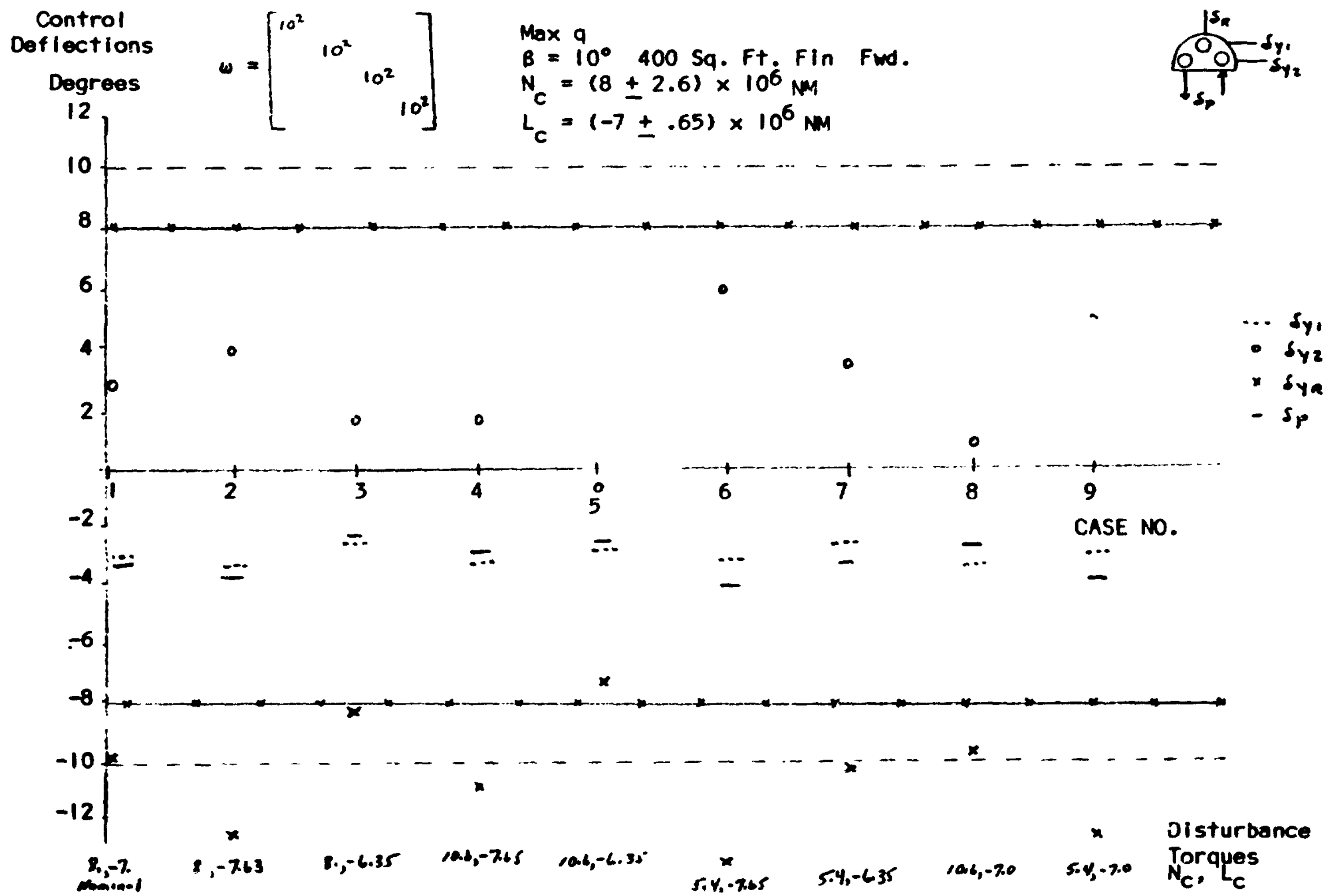


Figure 42. Engine deflections vs SRM misalignment disturbances — weighting effects.

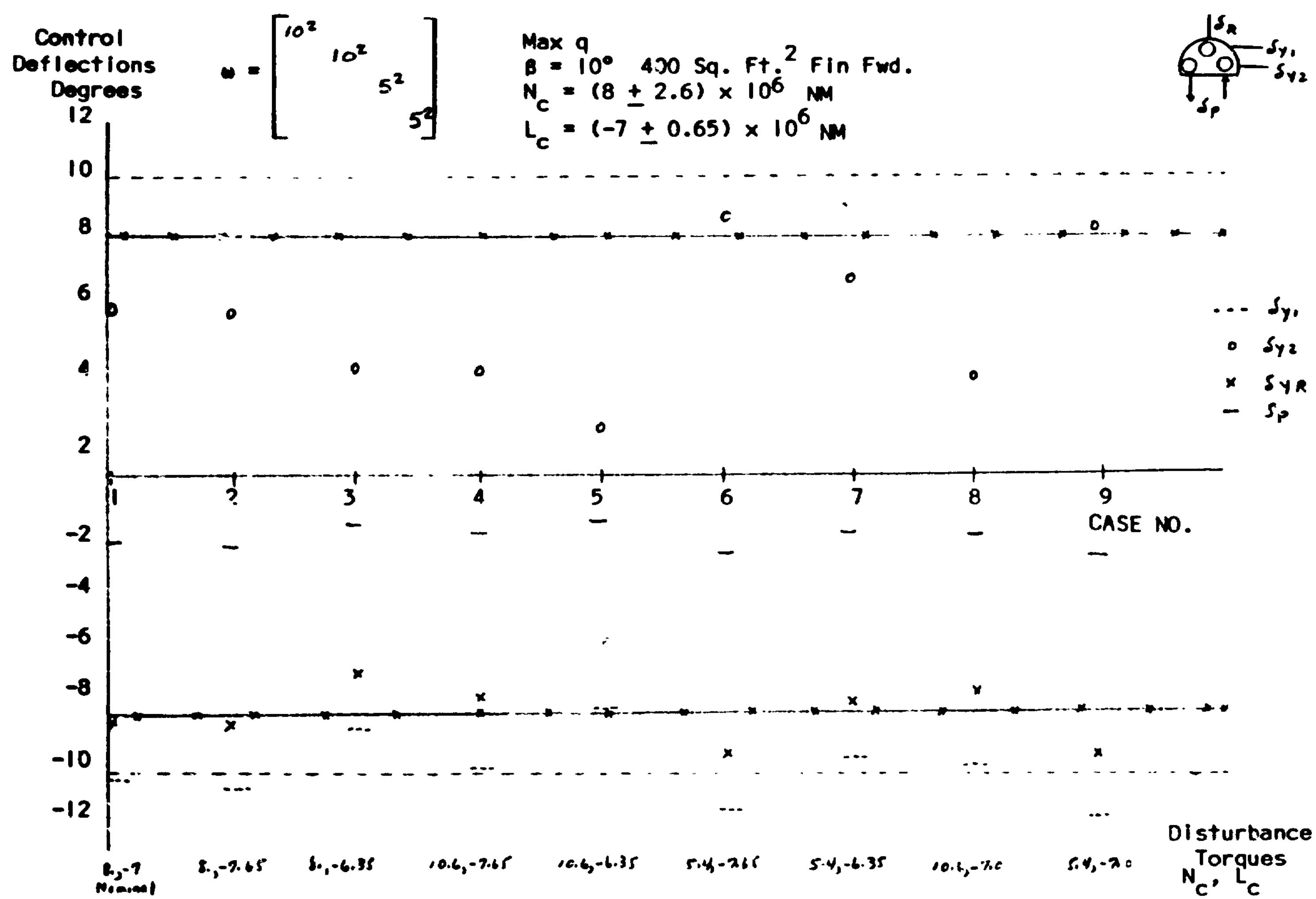


Figure 43. Engine deflections vs SRM misalignment disturbances — weighting effects.

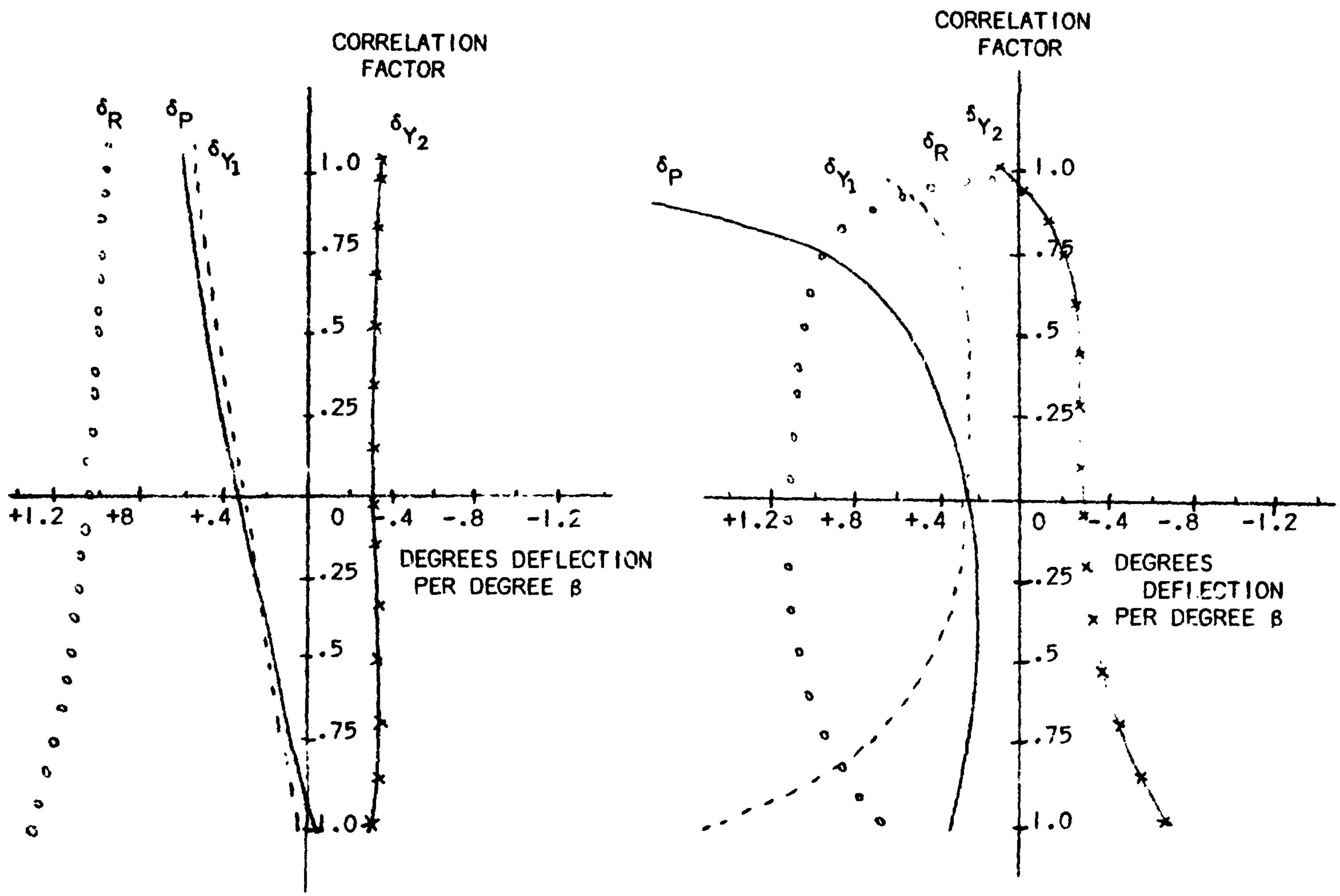


Figure 44. Correlating effects of the MOSES system.

c. Dynamic Response Results. The dynamic response of the two types of blenders on the 049 configuration was determined by 6-D simulation and several of the variables have been listed on Figure 45 for comparison. Blender A of the figure utilized the quadratic performance index while Blender B used the averaged vehicle characteristics. Both types of blending produced very adequate responses to the 60 m/sec crosswind for the perfectly aligned case. The performance index blender, however, showed superiority both in control and effector deflections used. This, of course, reflects the procedure of optimizing Blender A continuously while the Blender B is for averaged characteristics. The continuous optimization procedure also allows for logic to be programmed in to account for saturation of individual effectors or for effects of some malfunctions such as engine out. Continued study is required to best take advantage of the possibilities of this technique.

5. EFFECTS OF AN INTEGRATED LIFTOFF/ASCENT WIND PROFILE

Preliminary studies on the shuttle configuration have revealed its high sensitivity to the SRM misalignments for the no SRM TVC case. Response to the misalignments produces high gimbal angle demands during early flight when initial trajectory maneuvering is being accomplished, and also during the period when the vehicle is passing through the altitude regions where there is transition between the boundary-layer-influenced ground winds and the free-atmospheric-flow ascent winds. Because of this high level of vehicle response during the transition time, the validity of the common practice of using two separate areas of analysis, i.e., lift-off and high q flight, for control system analysis, has to be questioned.

The need for an integrated analysis for control system and performance studies brought about the need, also, for a definition of an integrated wind profile which merged the ground wind profiles with those of the inflight winds. This profile has, therefore, been developed and is documented[7]. In this memorandum, ground wind buildup envelopes, shears, and gusts are defined, along with the recommended methods for blending into the high altitude winds. Each of the different buildups, i.e., shears and gust envelope, or envelope plus gust, (see Figure 46), must be examined to determine which causes the worst case for the most critical variables. Previous vehicles (Saturn V), where drift was a significant problem, showed most sensitivity to the envelope plus gust type of winds. The rotational response, however, is more a problem to the shuttle configurations than drift, and preliminary results indicate that the shears plus gust produce a significantly greater response, particularly in roll and engine deflections. Early roll responses to shear and gust buildup

7. George H. Fichtl, Merged Space Shuttle Design Ground and Inflight Wind Profiles for Systems Trade-off Studies, S&E-AERO-YA, October 24, 1972.

BLENDER A — QUADRATIC PERFORMANCE INDEX
BLENDER B -- AVERAGED VEHICLE CHARACTERISTICS

SRM MISALIGNMENT	ϕ	δ_P	δ_Y	δ_{RUD}	ψ
DISTURBANCE (NONE)					
BLENDER A	0.44°	-4.8°	-4.1°	-6.0	-0.16
BLENDER B	4.0°	2.0	3.2°	10.0	3.0
ROLL 0.7×10^6 YAW 2.5×10^6 (N-M)					
BLENDER A	0.5	-4.8	-5.1	-6.3	-0.20
BLENDER B	12.0	8.0	8.0	10.0	4.0
ROLL 0.87×10^6 (N-M) YAW 0					
BLENDER A	0.52°	-6.2	-4.3	8.44	0.16
BLENDER B	8.0°	8.0	8.0	10.0	3.0°
ROLL 0.0×10^6 (N-M) YAW 3.0×10^6 (N-M)					
BLENDER A	0.45°	-6.2	-7.8	-4.2	0.21
BLENDER B	8.0	8.4	8.4	10.0	4.0

Figure 45. Compaıison of blender dynamic response.

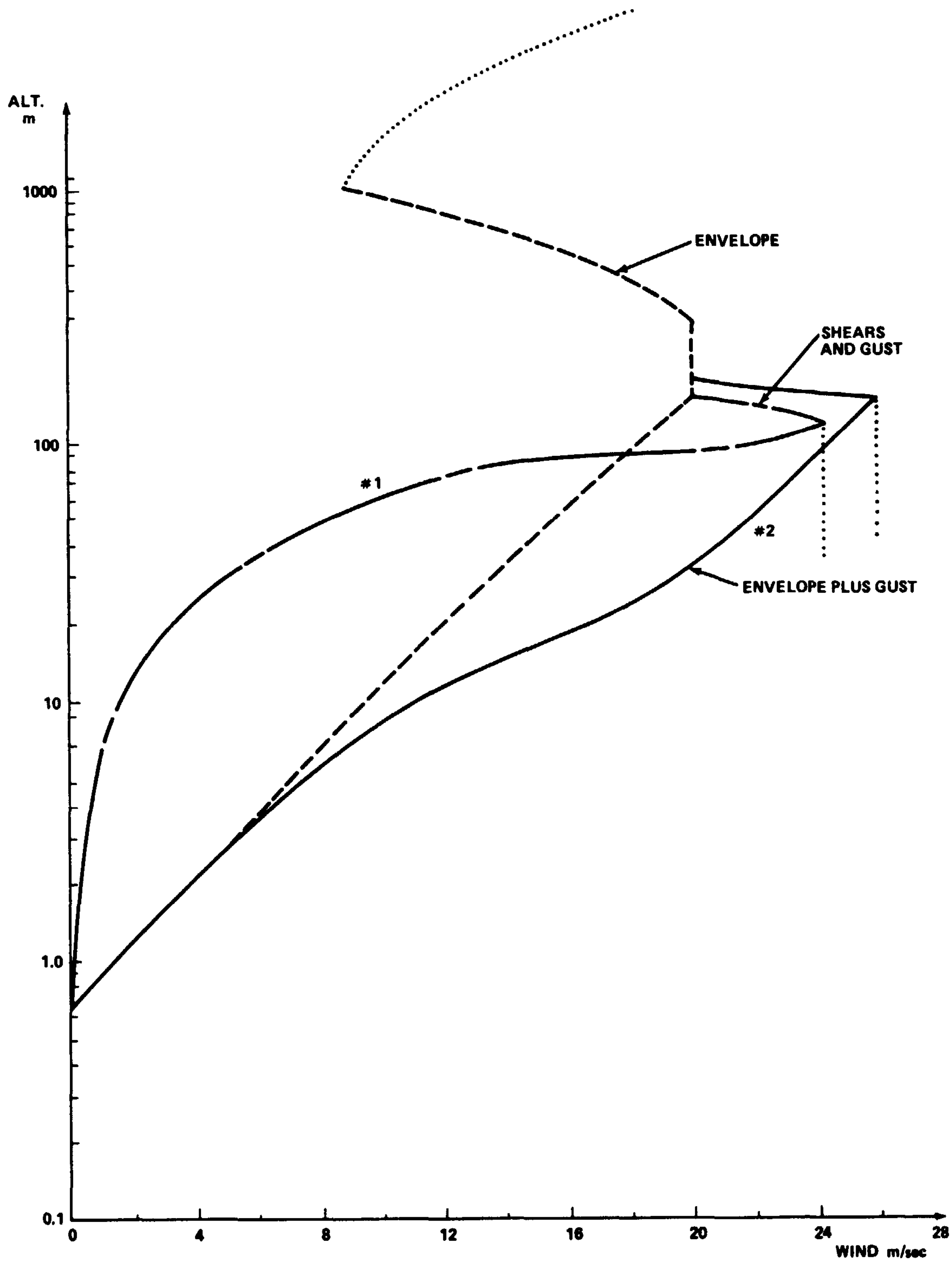


Figure 46. Space Shuttle lift-off winds.

(profile #1, Figure 46) may be compared to those of an envelope plus gust (profile #2, Figure 46) by examining Figures 47 and 48 which represent cases in which only the wind profile was changed.

Engine deflections display similar trends with respect to ground wind profiles, as indicated by comparison of Figures 49 and 50. These comparisons support the conclusions above that the shear wind buildup produces the more significant responses. One important aspect of the shuttle flight is the establishment of a good trajectory with minimum error early in flight, where the vehicle flight is quite sensitive to trajectory errors. Ground winds, of course, perturb the initiation of the trajectory and can, therefore, have some effect on the achievement of its performance values. The condition of the vehicle state at any given point, after the transients due to misalignments and winds, must be evaluated with respect to continued ability to perform the mission. Thus, it is imperative that an integrated profile be used to assure that the early states achieved by response to ground winds and misalignments do not lead to later problems with control, loads or performance. Evaluation of these profiles on the shuttle has not been made in preceding work, but their importance is quite apparent.

6. ABORT CONSIDERATIONS

Abort mission ground rules are still being studied and lead to depth of analyses far beyond the scope of the studies reported here. Nevertheless, certain results obtained are pertinent to the abort considerations and should be reported. In the process of the study, a maximum SRB misalignment tolerance of one half of a degree has been established if SRB TVC is not utilized. If greater SRB misalignments do occur, an aborted mission is assumed because of excessive response and performance loss. These cases, however, also need to be examined to determine if any other constraint which might be injurous to crew or vehicle integrity exists. Accordingly, studies were made on the ATP vehicle for larger than one half degree misalignments and the results of interest have been briefly discussed in the Executive Summary and are shown in more detail in Figures 51, 52 and 53. These plots show how the maximum value of the product of sideslip angle and dynamic pressure ($q\beta$), the roll rate (P), and the product of roll rate and dynamic pressure (qP) vary as the SRB misalignment increases. The $q\beta$ product is a load indicator and is currently baselined at 5100 PSF-deg. Assuming a 1.4 safety factor, the failure point would occur at 7140 PSF-deg (the top line). For these pure yaw misalignments greater than $.5^\circ$, the rate of increase of maximum $q\beta$ becomes quite high and the point of failure is reached in the .75 degree misalignment range. As indicated, these values can be changed

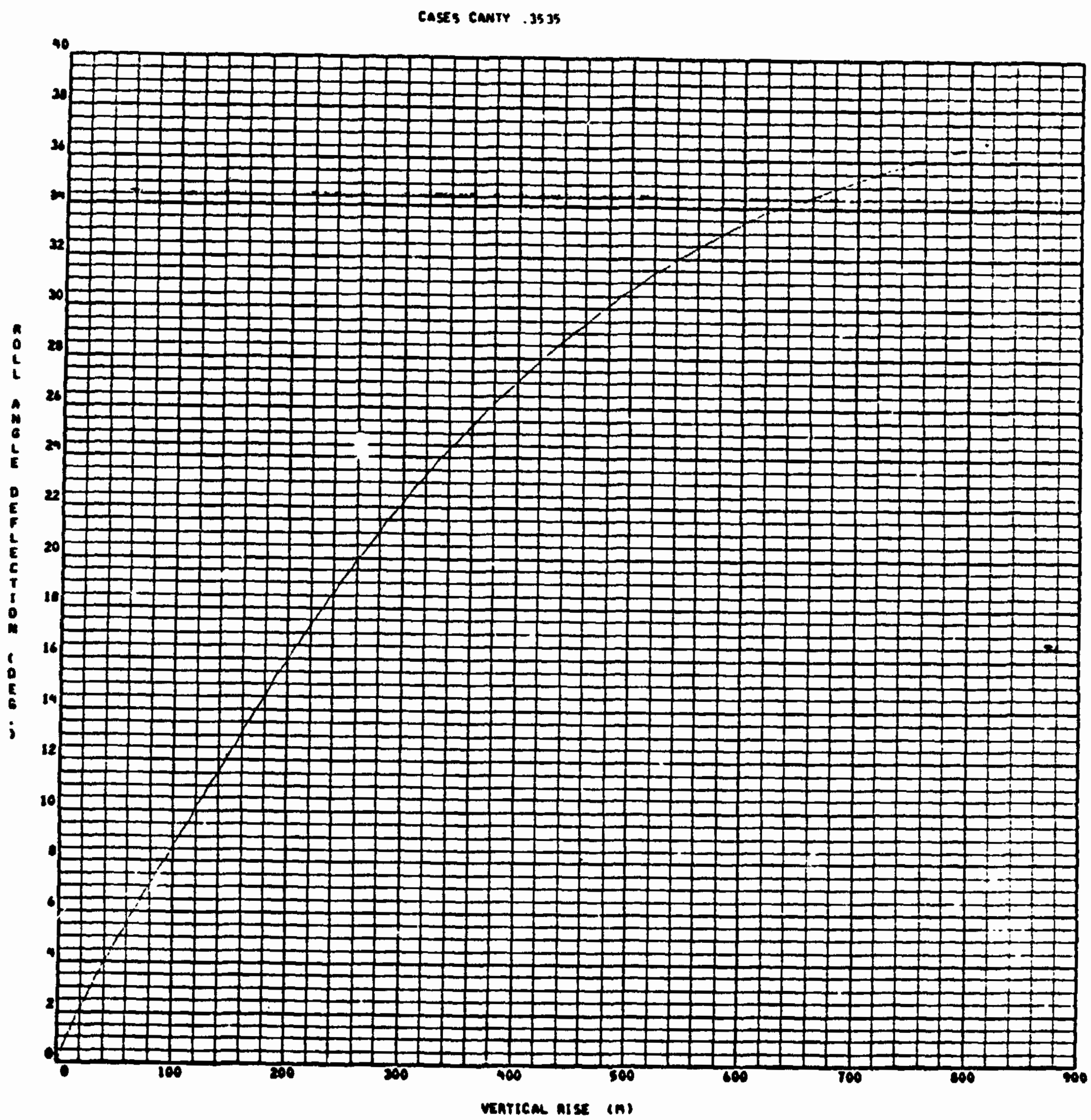


Figure 47. Roll response to shear and gust buildup.

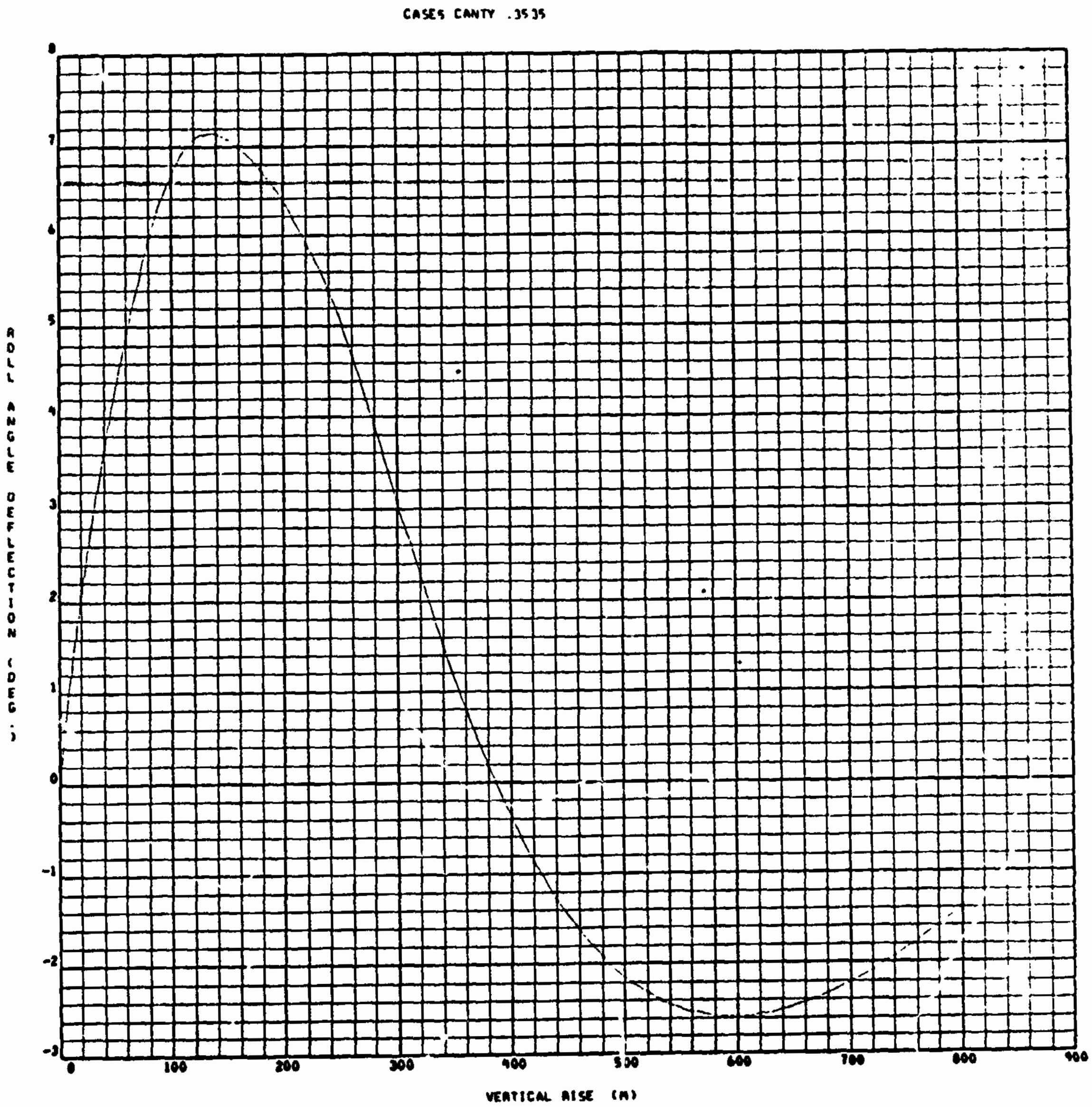


Figure 48. Roll response to envelope plus gust.

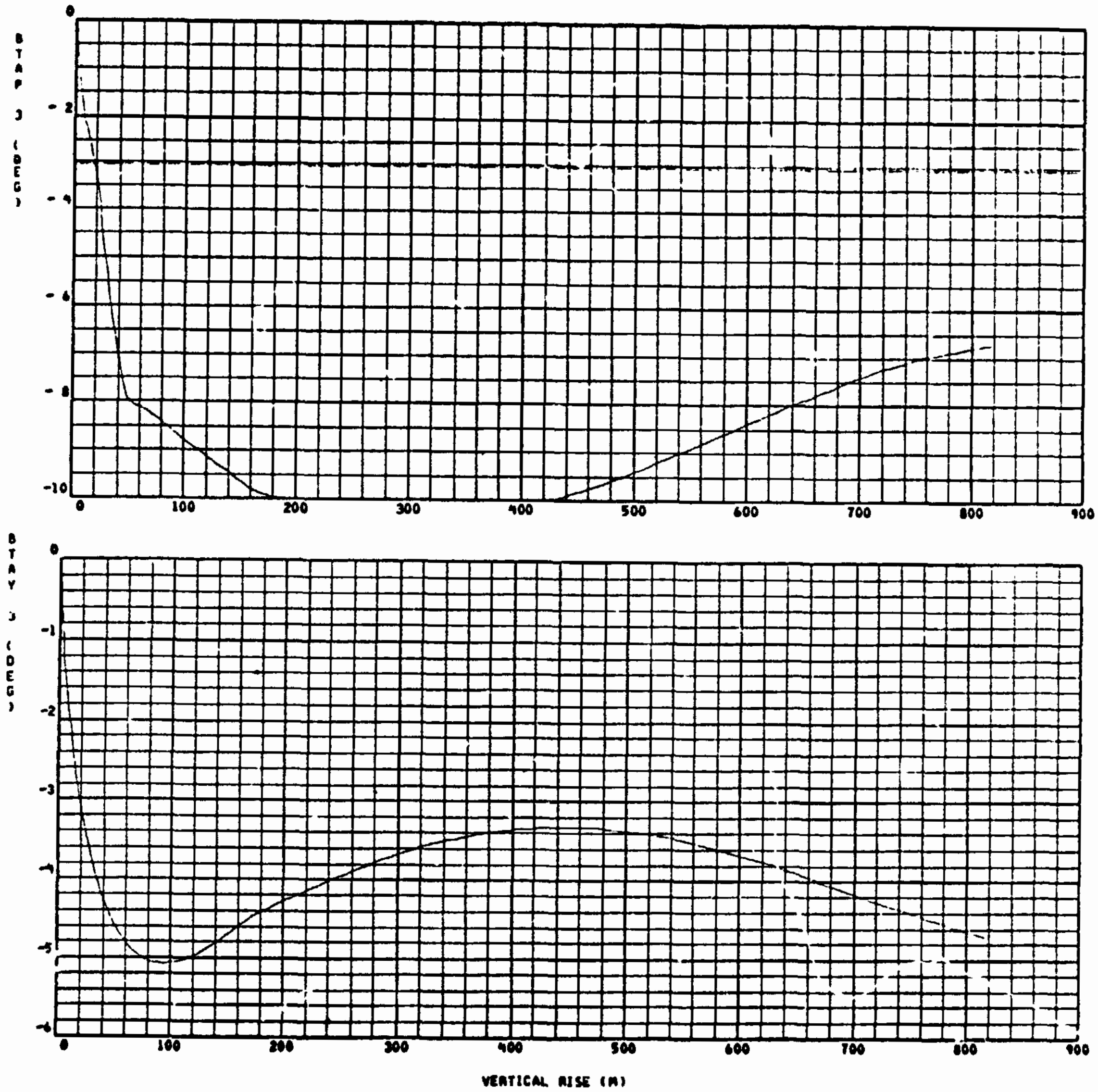


Figure 49. Engine deflection from shear and gust buildup.

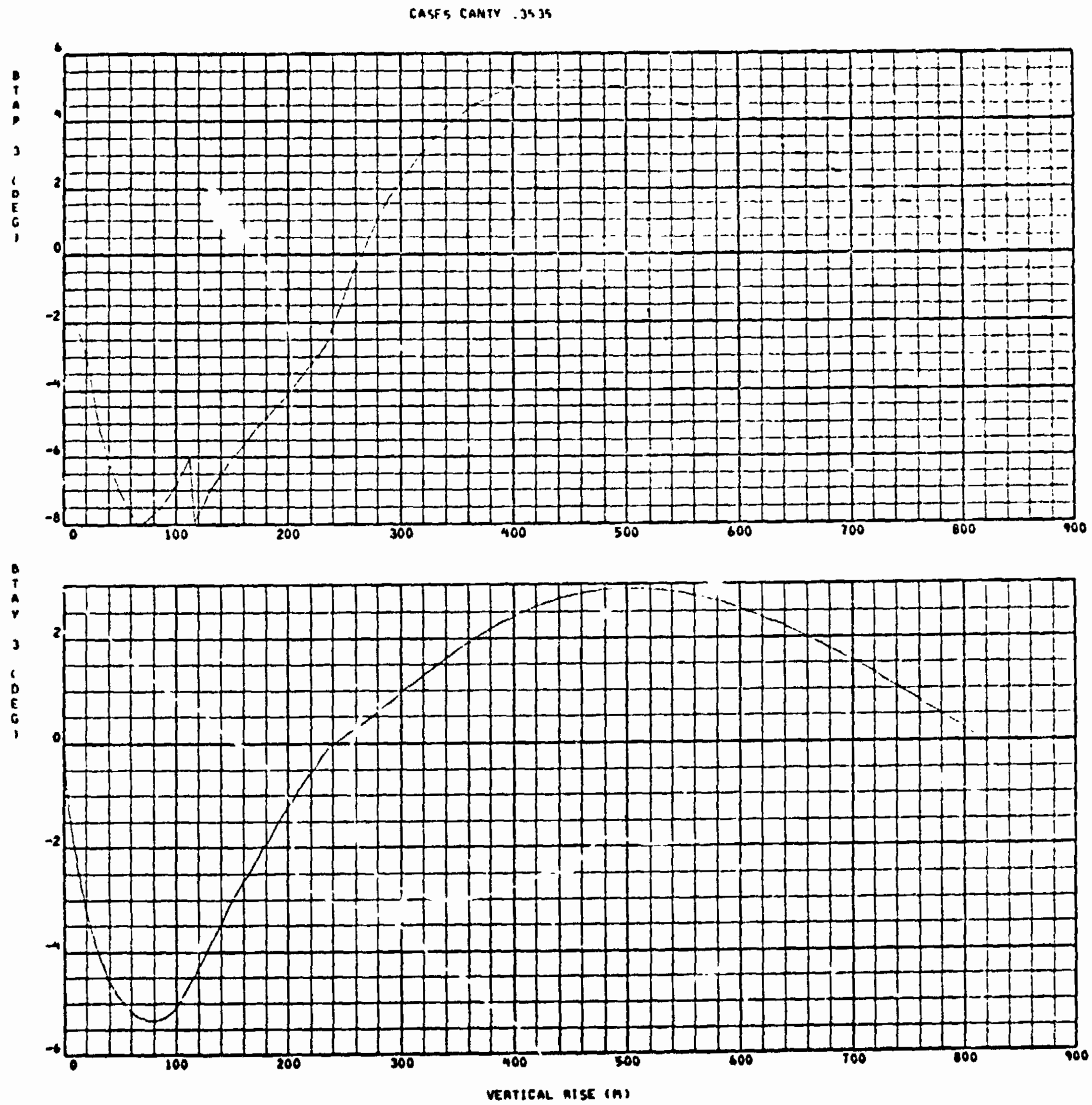


Figure 50. Engine deflection from envelope plus gust.

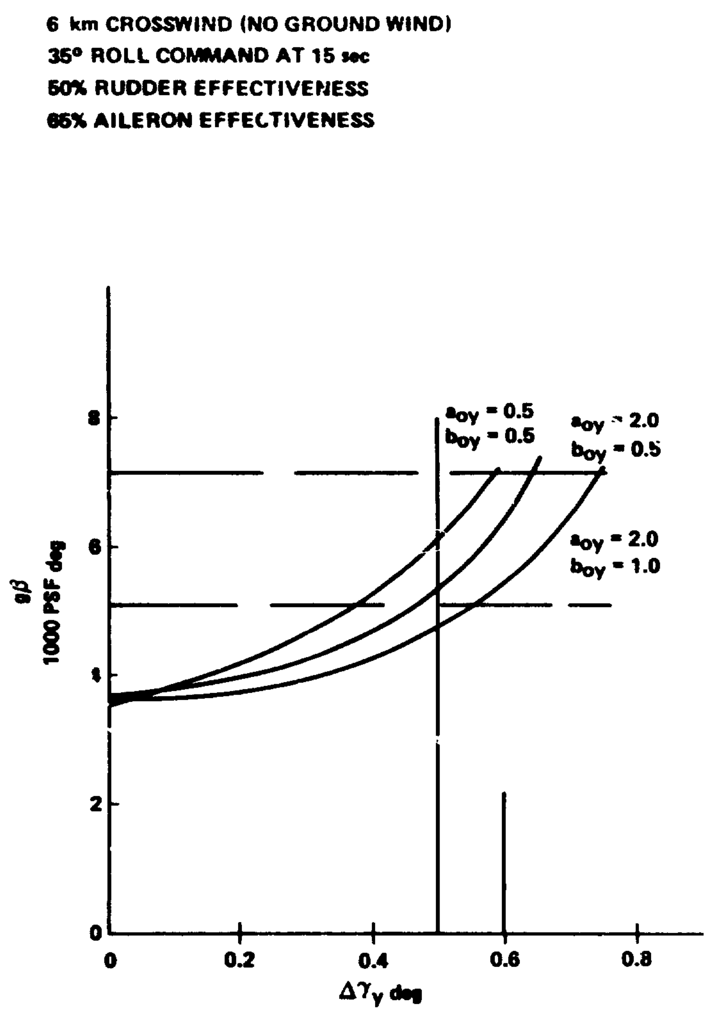


Figure 51. Load factor response to misalignment on SRB.

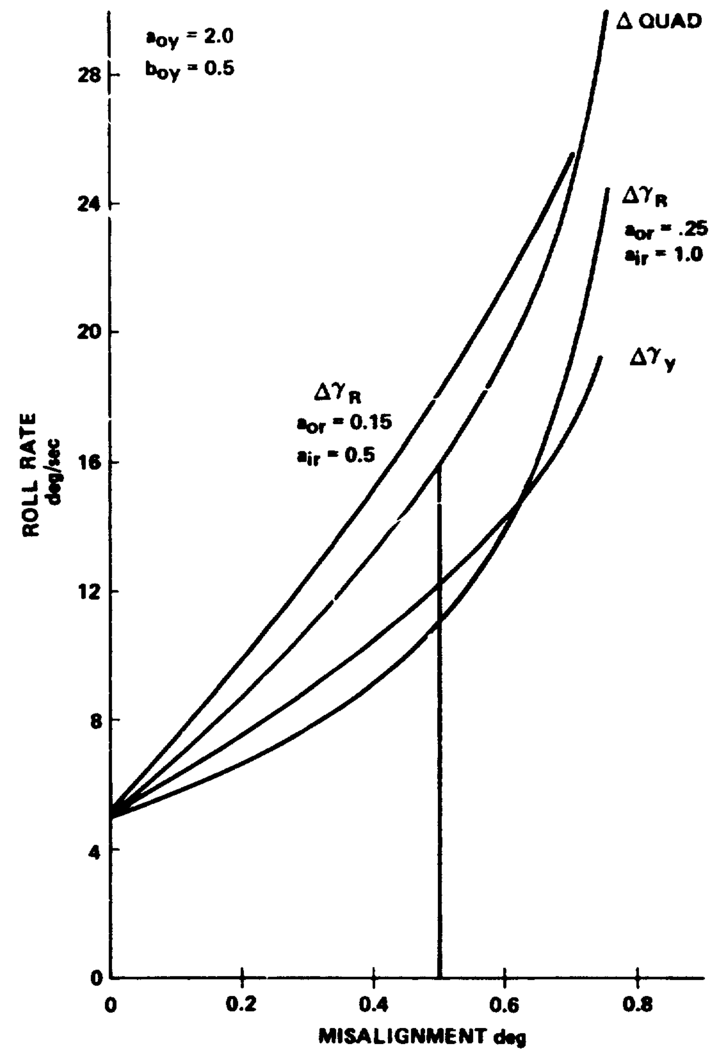


Figure 52. Roll rate response to misalignment on SRB.

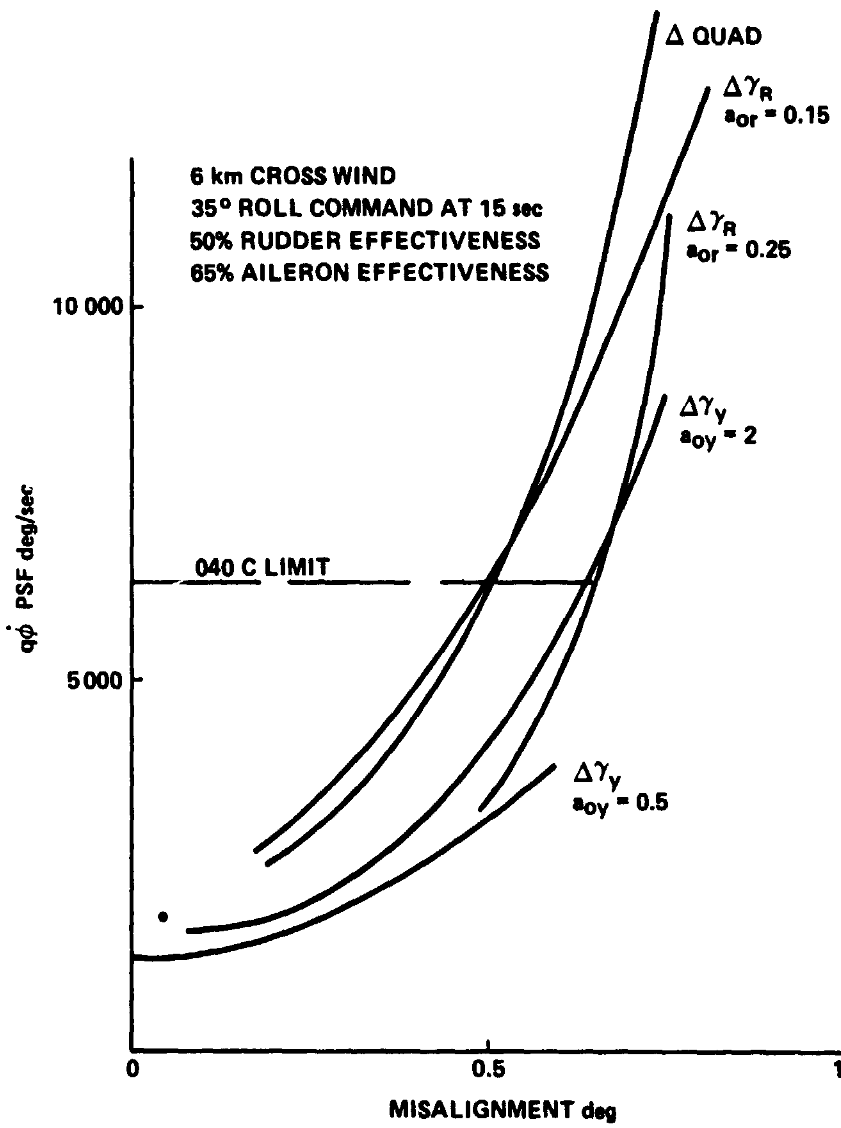


Figure 53. qP response to greater than 1° misalignment on SRB.

somewhat by the type of control system that is being flown. A higher load relief system (b_0 greater) will reduce the $q\beta$ magnitudes but will also affect the vehicle performance adversely because of its tendency to deviate from the path as it reduced the sideslip angle. The third curve points out the need to maintain a relatively high path angle gain for better margin. These observations point out the probable need to change control logic toward higher load relief when the need for mission abort is recognized. The abort recognition, however, presents another problem. Because of the control characteristics of this vehicle, without SRB TVC large transients are expected to occur due to fast changing vehicle response to acceptable misalignments. Cues that will establish that a vehicle is experiencing a larger than acceptable misalignment — not merely the transient from an acceptable misalignment — in time to get logic switched and initiate action in time to prevent breakup will be difficult to formulate. Dynamic responses, shown in Figure 54, reveal that the $q\beta$ time histories can go from near design value to the failure value due to wind gusts, which take but a few seconds to develop. Warning time is, therefore, very short. This again points to a dilemma in the control system design: Increasing the gains to achieve good vehicle response causes control system saturation in response to the SRB misalignments.

Maximum roll rate is plotted versus misalignment value for several types of misalignments and two sets of control gains for one of the misalignments. (See Figure 52.) These rates occur early in flight when misalignments are being trimmed and the roll maneuver is being performed. The shape of the curve also reflects the trends mentioned with respect to the $q\beta$ product, namely, the rate of increase is quite sharp above a half degree misalignment with the values becoming quite large. No maximum allowable magnitude has been established for the ATP vehicle but the higher values may become quite disturbing to the pilots. Increase in the roll gains at the expense of early engine saturation still results in considerable rates for misalignments above one half degree. An earlier shuttle version had a dynamic pressure, roll rate product limit of 6300 PSF deg/sec placed on it[8] so the ATP qP product was plotted against this limit, as shown on Figure 53, for the same cases as the previous figure. Using this criterion, the plot also shows that larger misalignment values than one half degree would be unacceptable.

The rate of increase in the response maximums of the variables just discussed, as the one half degree misalignment is exceeded, points up again the marginality of a control system that does not include SRB TVC. With the large excursion values for intolerance response, recognition of a malfunctioned or an out-of-tolerance flight becomes exceedingly difficult.

8. C. T. Modlin, Jr., Wing Aerodynamic Load Limits for the Parallel Burn Launch Configuration, MSC-ES2, April 5, 1972.

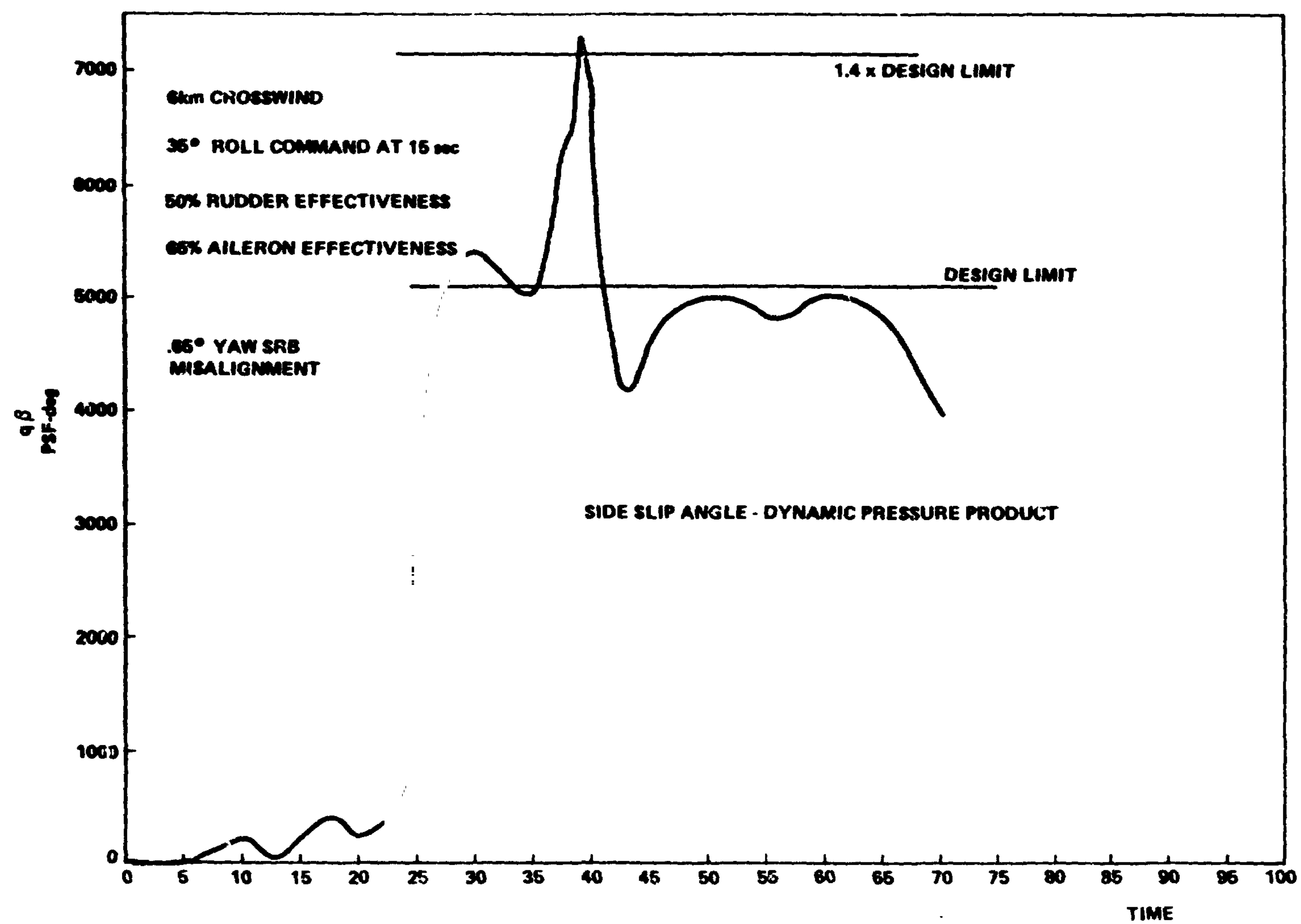


Figure 54. $q\beta$ time history.

As mentioned previously, many more factors must be considered for abort than have been touched on here. Nevertheless, the identification problem will be very real in light of the rapidity in which the load indicators can change the wind gusts.

7. GENERAL TREND STUDIES

Several general trend studies important to overall systems considerations were performed using 049 vehicle data. The trend information thus obtained can be extrapolated to the other configurations of similar geometry. In these trend studies the effects on stability and control due to (1) addition of fins, (2) variation of shape of trajectory and of orbiter orientation, (3) change in SRB pitch cant angle, and (4) change in relative direction at which the wind strikes the vehicle have been determined. Results obtained in each case will now be discussed.

a. Fin Study. Another possible method of improving the control situation in the high dynamic pressure regions is to alter the vehicle aerodynamic configuration so that the disturbances due to sideslip produce a moment vector which is reduced in magnitude and is more nearly collinear with the major control vectors. A study was made using a ventral fin attached to the HO tank as a means of accomplishing this. Since the vehicle was excessively stable in yaw, even without the fin, aft placement seemed inadvisable. Different fin sizes and fin placements, as shown on Figure 55, were considered. Control logic was chosen to give a control vector, also shown on the Figure 55, and a performance index consisting of the perpendicular distance of the disturbance vector from collinearity with the control vector was calculated.

Disturbance vectors (per degree sideslip), the control vectors (per degree), and the performance index were calculated over the flight time/Mach number range for the various fin sizes and locations. Figure 56 and 57 show the resulting moment maps over the flight time range. A 400 square foot fin located at either X = 1251 or 1451 shows up as most promising from these plots and this judgment is reinforced by the performance index, as shown for the better size/location combination on Figure 58. Another significant factor for consideration is that the X = 1251 location places the fin between the LOX and hydrogen tanks of the HO tank. This is a very convenient attach point from structural considerations.

Another small advantage, gained by use of the fins, is found in comparison of Figures 59 and 60. These figure show the movement of the system roots with Mach number. Comparatively less root movement is found for the

CODE NO.	FIN AREA (FT^2)	FIN LOCATION IN. FWD. GIMBAL PLANE
1	NO FIN	---
2	200	851
3	200	1251
4	400	851
5	400	1051
6	400	1251
7	400	1451
8	600	1251

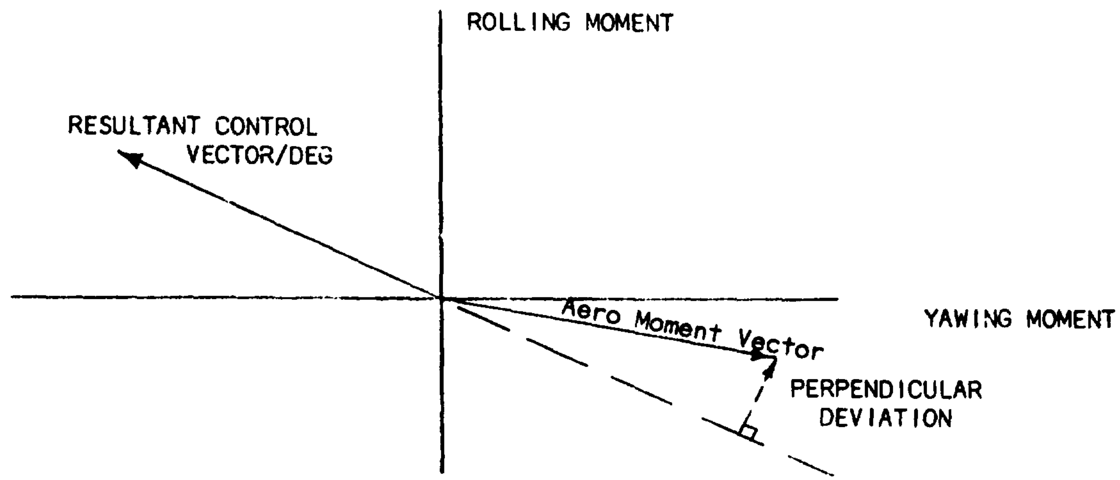


Figure 55. Fin study.

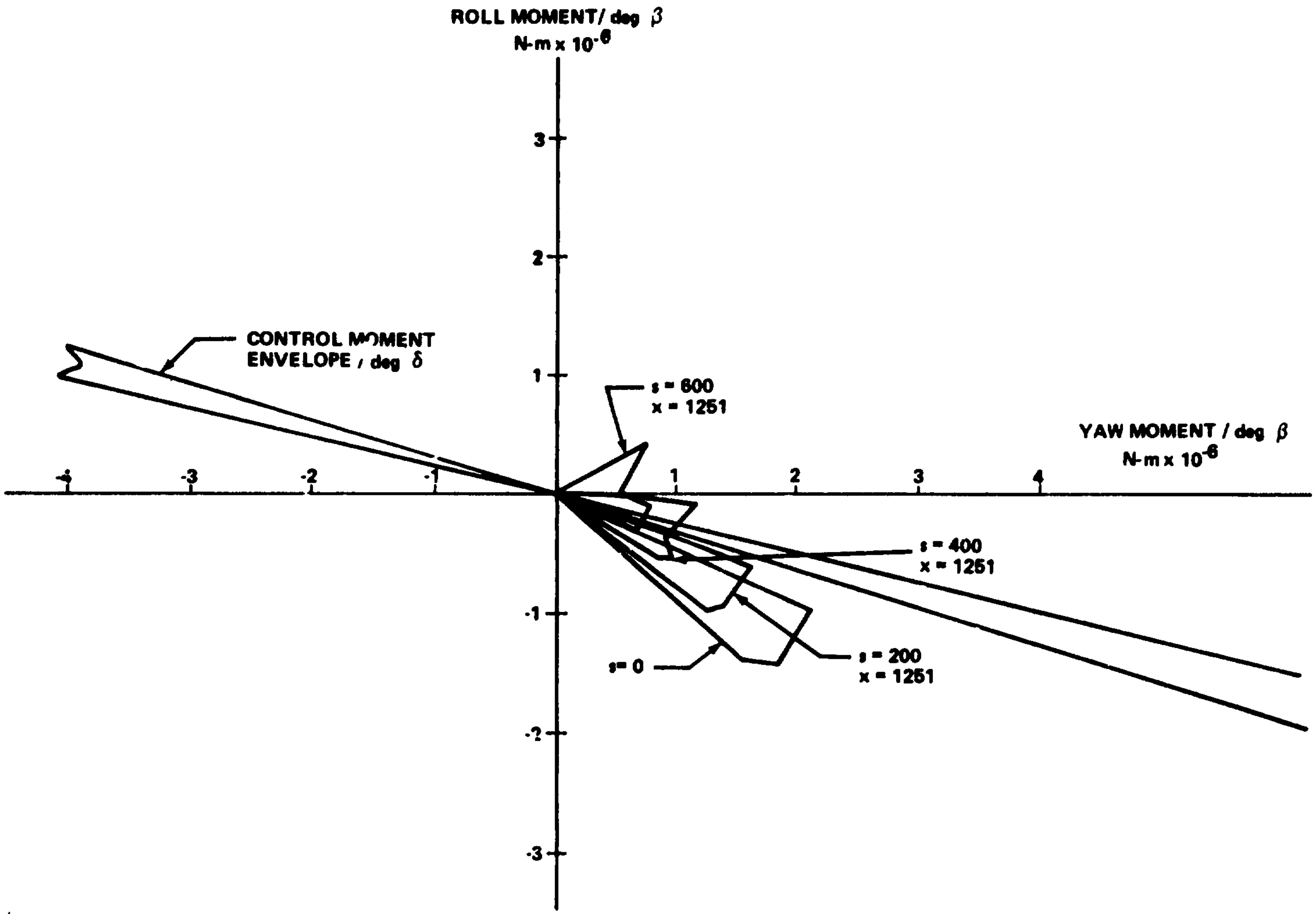


Figure 56. Moment map over flight time range for various fin sizes.

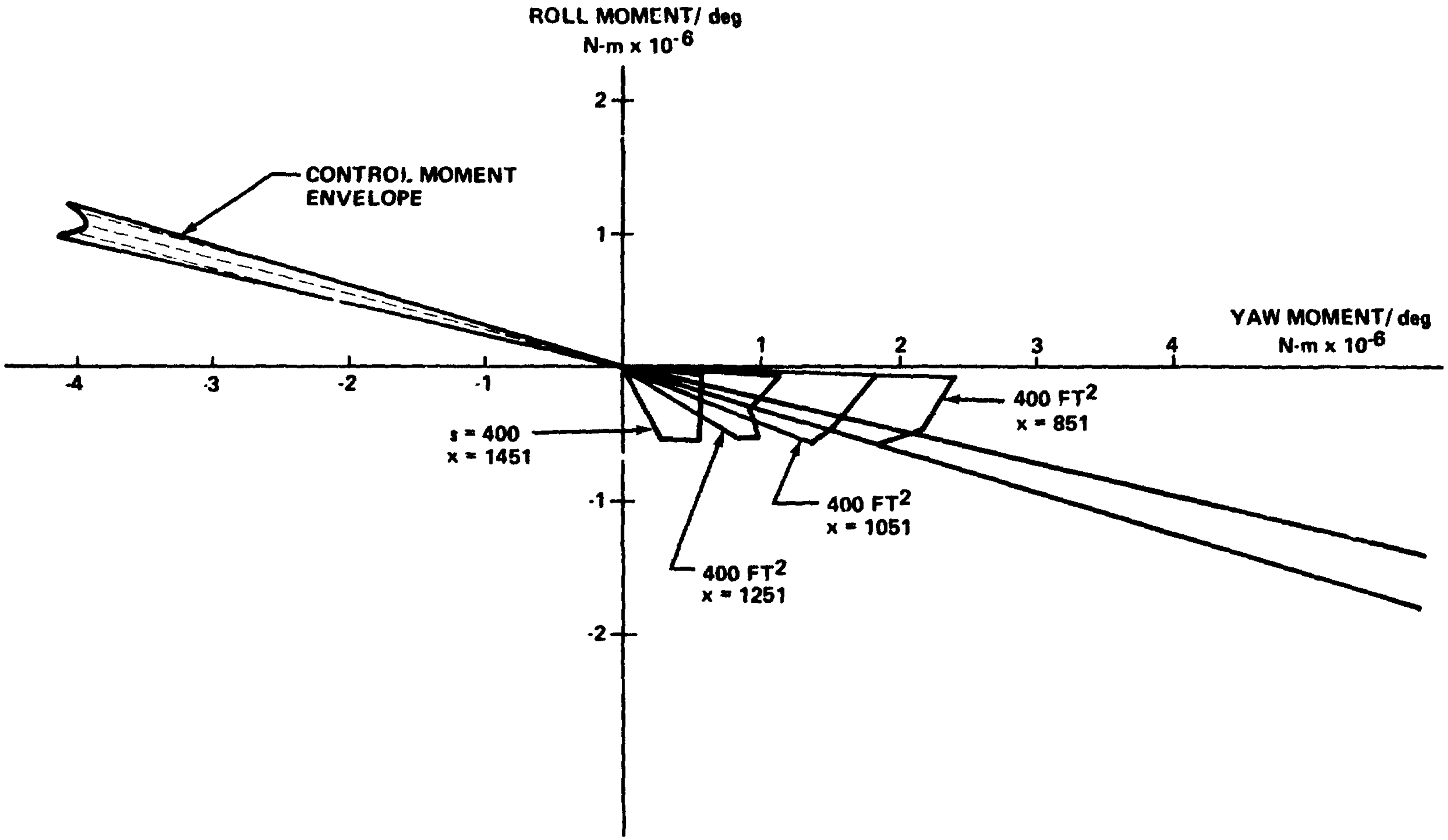


Figure 57. Moment map over flight time range for various locations.

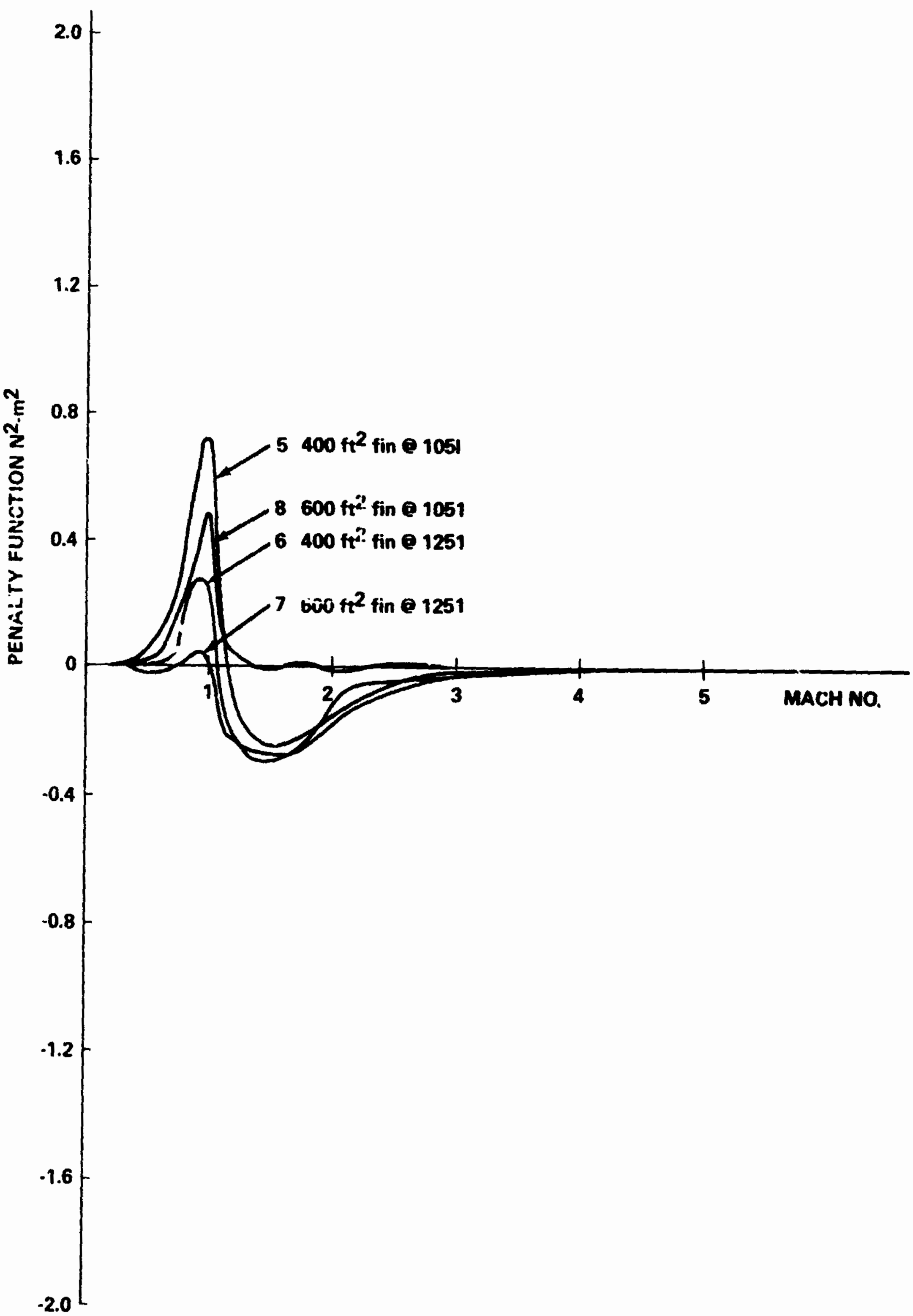


Figure 58. Size/location combination for performance inlet.

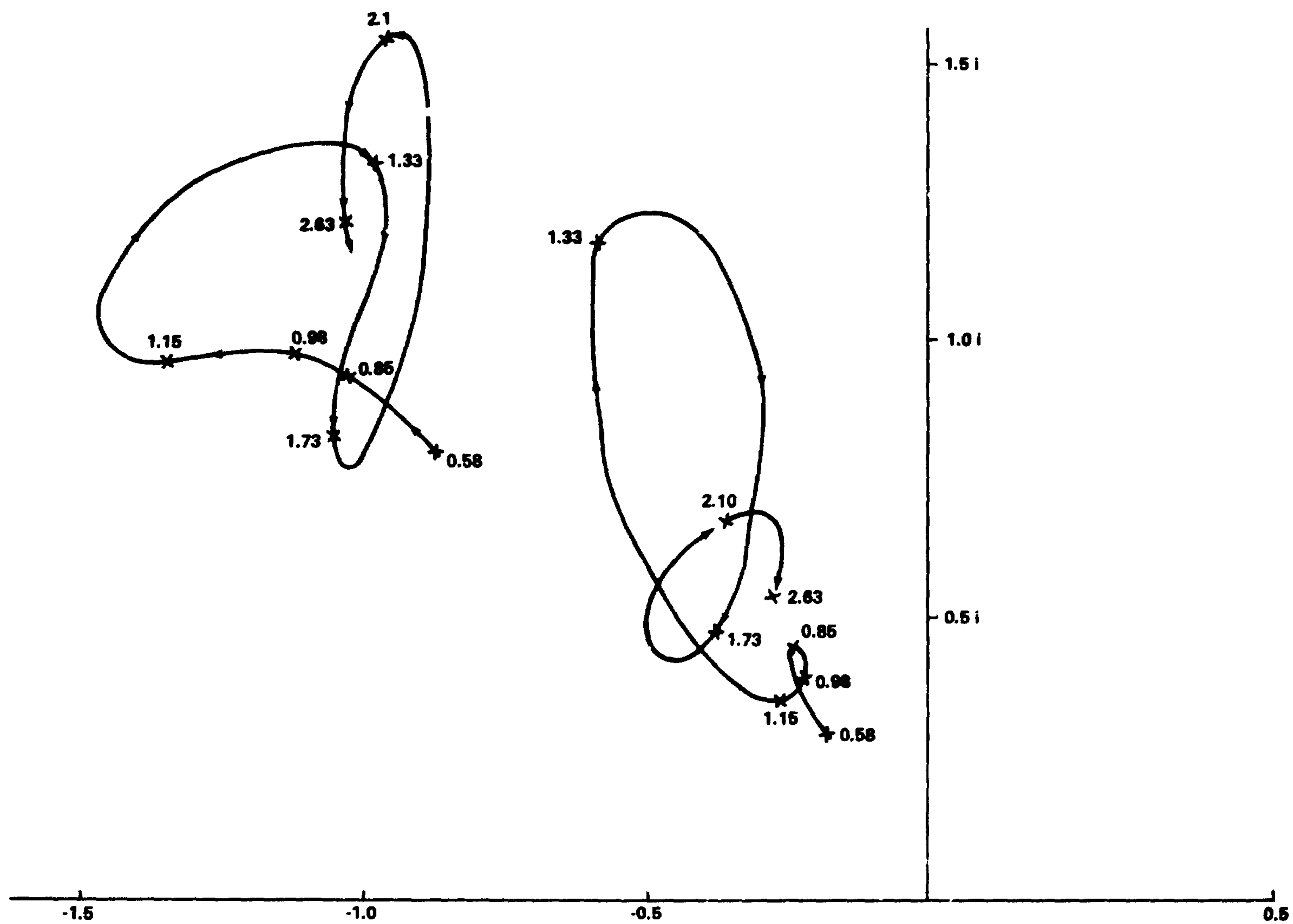


Figure 59. Basic vehicle root motion with Mach no. (no fin).

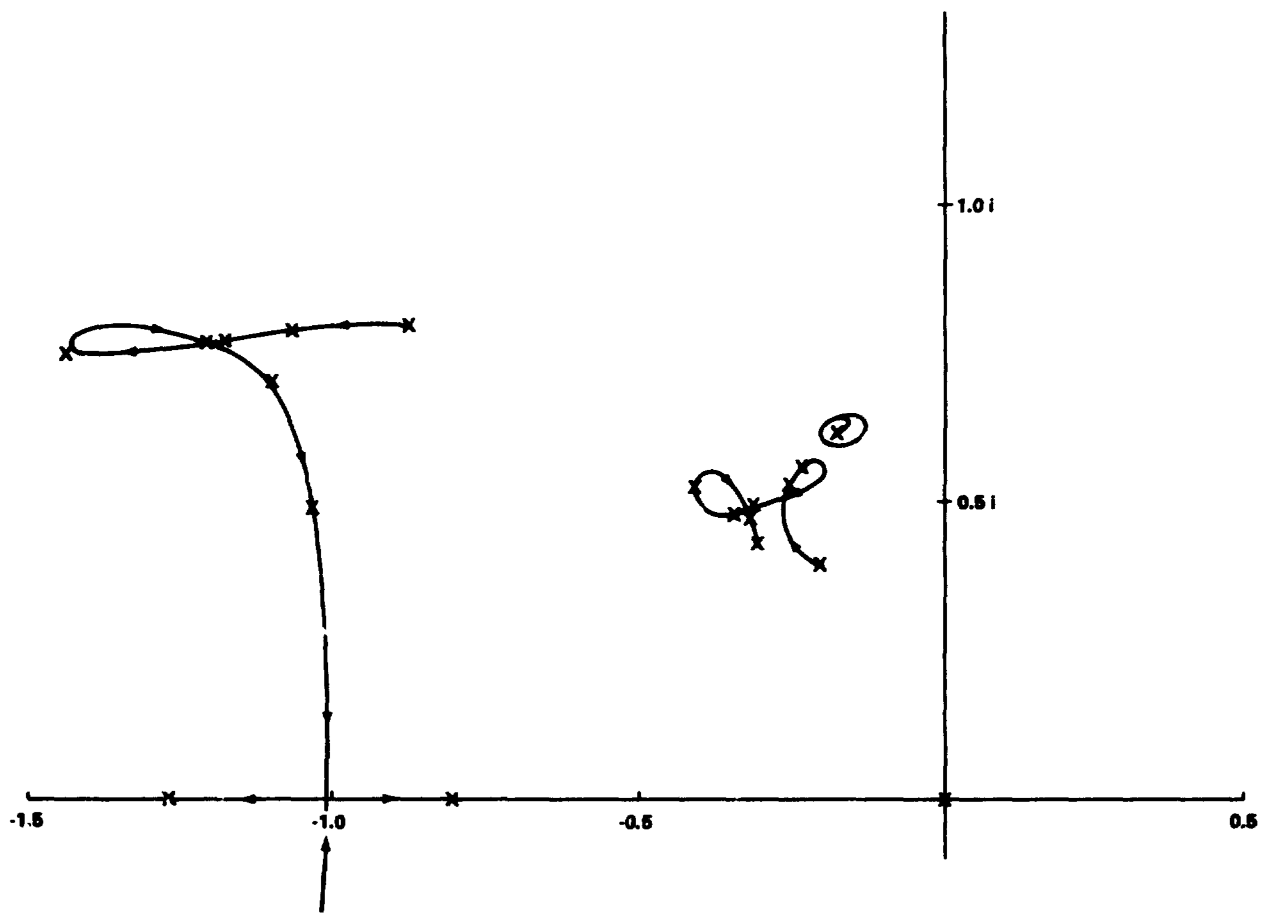


Figure 60. Basic vehicle root motion with Mach No. (fin).

system with the ventral fin. This tends to imply less sensitivity to gain variations once the roots are placed at their desired locations.

Additional fin data are shown on Figure 61 which lists the high dynamic pressure region control effector trim requirements for an 8° sideslip angle with SRM misalignments. Again, the 400 square foot fin located forward on the tank proves superior to the other configurations.

b. Trajectory and Orbiter Orientation Trades. Various types of trajectories were investigated for the 049 configuration and are summarized, from a payload standpoint, on Figure 62 which was obtained from the document cited in footnote 9. Payload effects can be derived from this figure, and reflect (a) change from point mass to moment balanced trajectories, (b) change in commanded angle of attack, (c) change in orbiter orientation, (d) change in SRM pitch cant, and (e) change due to envelope winds. The moment balanced, zero aerodynamic normal force, cockpit up trajectory serves as the baseline case.

The cockpit down, negative one degree angle of attack shows the payload advantage of this option over the others studied. The delta weights at insertion are also shown on Figure 62. For the heads up (cockpit up) trajectory the aerodynamic and engine normal forces are opposing each other as illustrated in Figure 63, with the predominant engine force tending to depress the trajectory. For the heads down trajectory, to the contrary, the engine normal force and the aerodynamic force work together to provide lift to the trajectory, which can be utilized to gain payload.

The influence on dynamics and control of the various effects of all the different cases for which the payload was displayed will not be discussed. However, Figure 64 is a presentation of several dynamic and control variables for both the "heads up" and the "heads down" trajectories. A 50-meter per second wind has been applied from several directions relative to the vehicle. Comparison of the various maximum quantities reveals that, while some differences do exist between the two ways of orienting the orbiter, none of the differences are significant enough to be sufficient to eliminate either orientation from consideration. Tilting over the wing required a considerable "dog leg" in the trajectory and did not show sufficient additional promise to be considered further. To expedite the other trend studies of the 049 configuration, which are reported upon herein, the "heads up" trajectory was chosen for continuing studies.

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9. Orval Ethridge, Moment Balance Trajectories for the MSC-049 Orbiter Configuration with Two 156" Solid Rocket Motors Burning In Parallel, S&E AERO-GT-55-72, June 15, 1972.

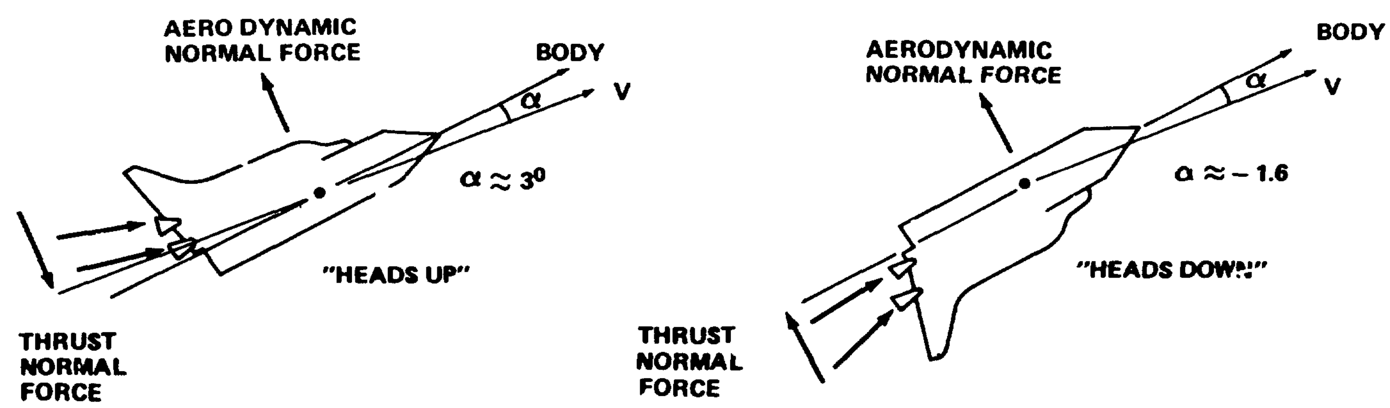
Conditions: Max q 8° Sideslip SRM Misalignments Fins 400 Sq. Ft. (forward & aft), 200 Sq. Ft. (forward & aft), No fin								
Fin Size	Minimum				Maximum			
	δ_{y_1}	δ_{y_2}	δ_R	δ_P	δ_{y_1}	δ_{y_2}	δ_R	δ_P
Nominal	9.9	3.0	12.1	7.9	11.6	7.9	15.2	10.5
200 Fwd.	7.4	2.2	9.0	5.8	9.1	7.1	12.2	8.4
400 Fwd.	4.8	0.9	5.8	3.7	6.5	5.8	8.9	6.3
200 Aft	6.1	4.1	4.0	1.2	7.8	9.0	7.2	3.8
400 Aft	2.0	15.6	0.97	2.85	3.7	21.0	4.1	5.4

Figure 61. Max Q trim requirements.

TRAJECTORY	VEHICLE ATTITUDE	(CASE - NOMINAL) Δ WEIGHT @ INSERTION
Zero Aero-Normal Force	Nominal Cockpit Up	0
Zero Aero-Normal Force	Cockpit Down	+ 3400 Lbs.
+ 1° Angle of Attack	Cockpit Up	+ 885 Lbs.
- 1° Angle of Attack	Cockpit Up	- 932 Lbs.
+ 1° Angle of Attack	Cockpit Down	+ 3232 Lbs.
- 1° Angle of Attack	Cockpit Down	+ 3513 Lbs.
Head Wind	Cockpit Up	+ 2727 Lbs.
Right Cross Wind	Cockpit Up	- 637 Lbs.
Tail Wind	Cockpit Up	- 3459 Lbs.
SRMS Canted Through C.G. Liftoff	Cockpit Up	- 2693 Lbs.
SRMS' Pitch Plane Cant Zero	Cockpit Up	- 1055 Lbs.
Pitch Over Wing	Cockpit @ 90° [a]	- 489 Lbs.
Point Mass Gravity Turn	Cockpit Up	+ 2467 Lbs.

a. Cockpit Up reference position angle measured from reference position to 180° Cockpit Down Position.

Figure 62. Summary of trajectories and corresponding payload.



AT 80 SECONDS:

THRUST CANT NORMAL FORCE (z)

HEADS UP $+1.65 \times 10^6$ **NEWTON**

HEADS DOWN $+1.65 \times 10^6$ **NEWTON**

AERODYNAMIC NORMAL FORCE (z)

HEADS UP $\alpha \approx 3^0$ $-.58 \times 10^6$ **NEWTON**

HEADS DOWN $\alpha \approx -1.63$ $+1.51 \times 10^6$ **NEWTON**

Figure 63. Basic force relationships for 049.

50 m/sec Wind										
	Heads Up					Heads Down				
Wind Dir.	No.	Left Cross	Left Quarter	Head	Tail	No.	Left Cross	Left Quarter	Head	Tail
q_{max} psf	428	455	472	391	391	488	518	540	545	411
$q\alpha_{tot\ max}$ psf deg	1443	4109	4135	3301	772	871	4508	3310	1846	2392
α_{max} deg	4.87	5.33	6.11	7.22	-6.24	-1.97	-4.23	-3.59	-4.25	6.34
β_{max} deg	0	-8.75	-6.72	0	0	0	8.97	6.5	0	0
Pitch Error max deg	-0.83	-1.69	-2.15	-2.92	4.5	-1.90	-2.74	-3.71	4.8	5.61
Yaw Error max deg	0	-10.8	-5.85	0	0	0	-16.28	-5.95	0	0
Roll Error max deg	0	27.3	19.73	0	0	0	-51.8	-34.9	0	0
$\delta_{p\ max}$ deg	1.74	10	10	6.02	-4.94	-1.62	-10	-10	-6.6	5.35
$\delta_{y\ max}$ deg	0	10	10	0	0	0	-10	-10	0	0
$\delta_{rud\ max}$ deg	0	10	8.9	0	0	0	-10	-10	0	0

Figure 64. Response data for heads up and heads down trajectories.

c. Cant Angle Studies. Effects of cant angles in pitch were also investigated. First, the no wind trajectories were run for various combinations of SRM cant and liquid engine cant. For determination of the liquid cants, the lower engine cant was specified and the upper engine pitch cant was varied to cause intersection with the lower engine thrust vectors at a point vertically above or below the c.g. The range in values for the pitch gimbal angle over the flight was plotted for that combination. Plots of engine deflection versus SRM cant are shown for two values of liquid engine cant in Figure 65. The magnitude of the range of pitch deflection values (envelope width) was recorded where the envelope was centered about zero. These and the corresponding SRM cant values were recorded and plotted in Figure 66, where the minimum range (1.78°) can be found, along with the corresponding liquid cant (13.2°) and SRM cant (.36°). It should be remembered that the values were picked that centered the gimbal range about zero for the no wind trajectory. Because of the difference in magnitude between the 95-percentile headwinds and tailwinds, this choice may not be the optimum case. No attempt was made, however, to redo the study in light of this difference. For continuing studies, a .34° SRM cant was used and the 12° /18° orbiter cants, as shown in the drawing of the 049 configuration, were used.

d. Wind Direction Influence. The effects of wind direction upon the control requirements were investigated by running trajectories with a 50-meter per second wind from different azimuths. Representative results are shown in Figure 67 which is a plot of the range of both the number one engine pitch and yaw deflections versus wind azimuth. The launch azimuth is oriented to 90° so that the 90° wind aximuth is a headwind and a 270° wind azimuth is a tailwind. These data suggest that the least excitation comes from a tailwind, and active load relief might be obtained by turning the tail into the wind.

e. Trajectory Shape Effect. The effects upon the required gimbal angle in pitch of changing the commanded angle of attack in the trajectory is shown in Figure 68. The α_0 trajectory at the origin commands the zero aerodyanmic normal force angle of attack and the plus one trajectory commands an additional degree of angle of attack over that of the α_0 trajectory. One portion of the figure shows the wind speed that just produces a 10° gimbal deflection for both headwinds and tailwinds for the values of pitch attitude error gain. The "softer" control system (a_{op} = .5) allows a larger wind speed without hitting the limits, but also allows greater attitude errors. The shift of the $\alpha_0 + 1$ trajectory provides a bias to offset the difference in magnitude between the 95% headwind and 95% tailwind and permits 95% wind capability. One of the prices paid for this, however, is illustrated in the other portion of the figure. The product of the dynamic pressure and the angle of attack, a

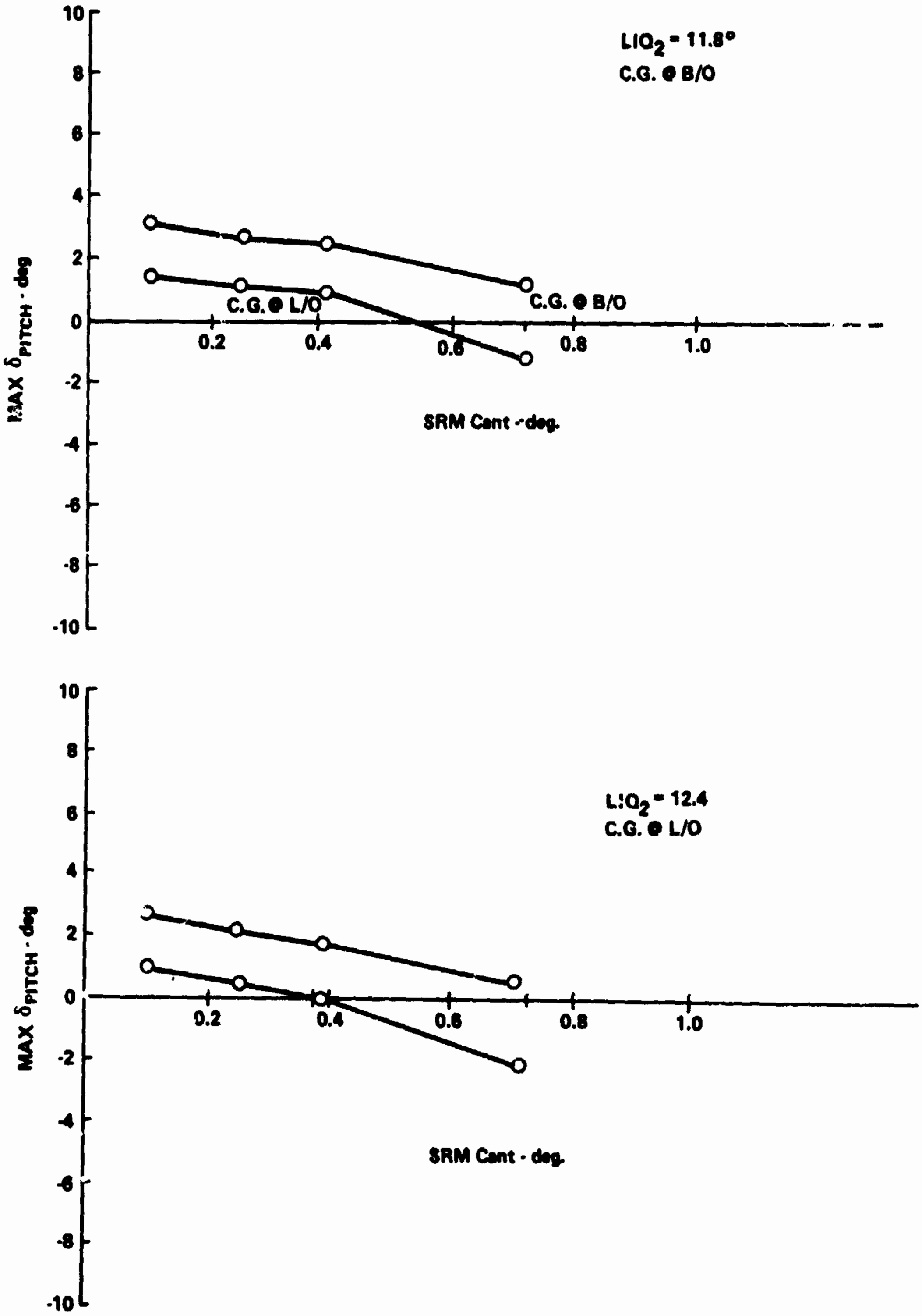


Figure 65. Maximum engine deflection envelope.

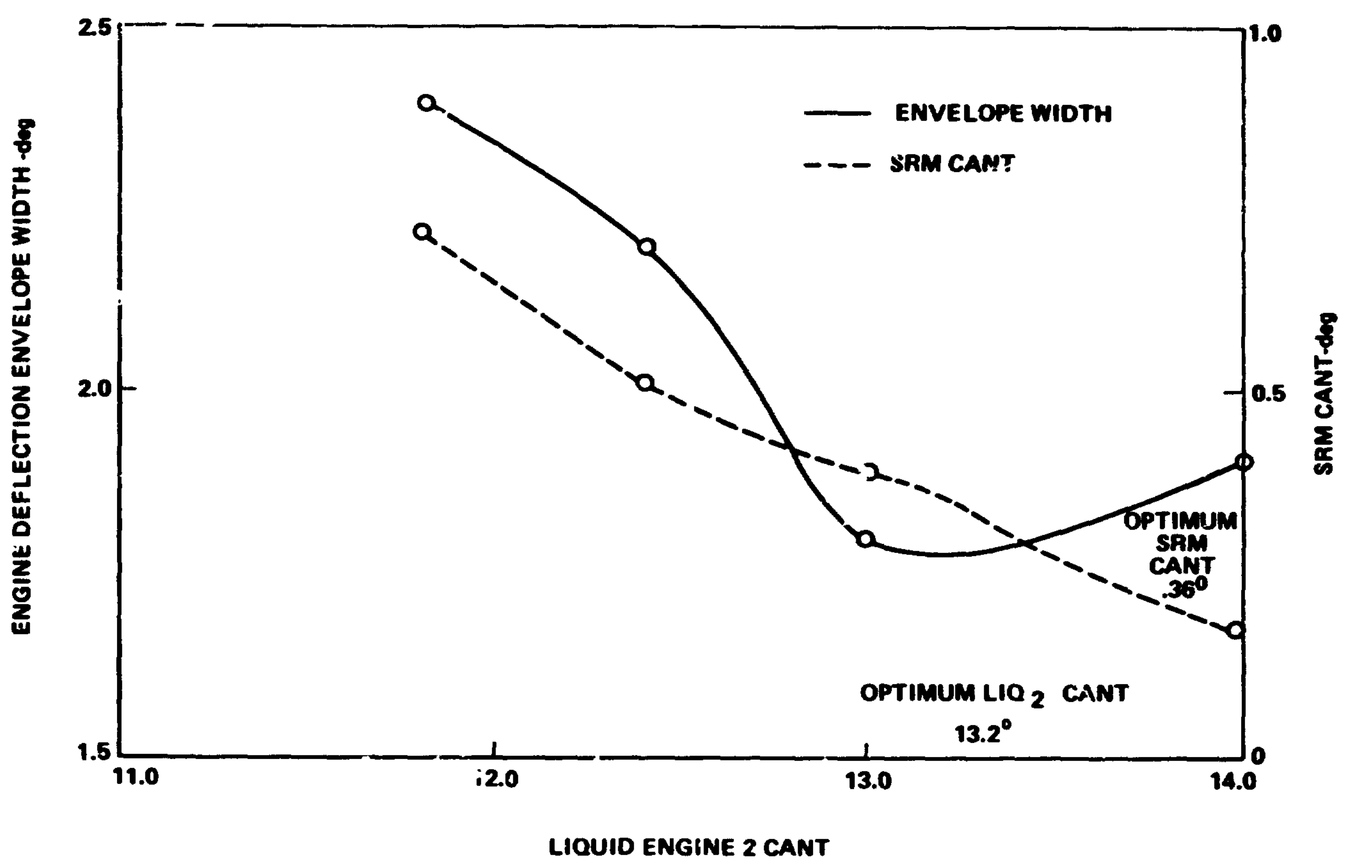


Figure 66. Envelope width and SRM cant for centered deflection envelope.

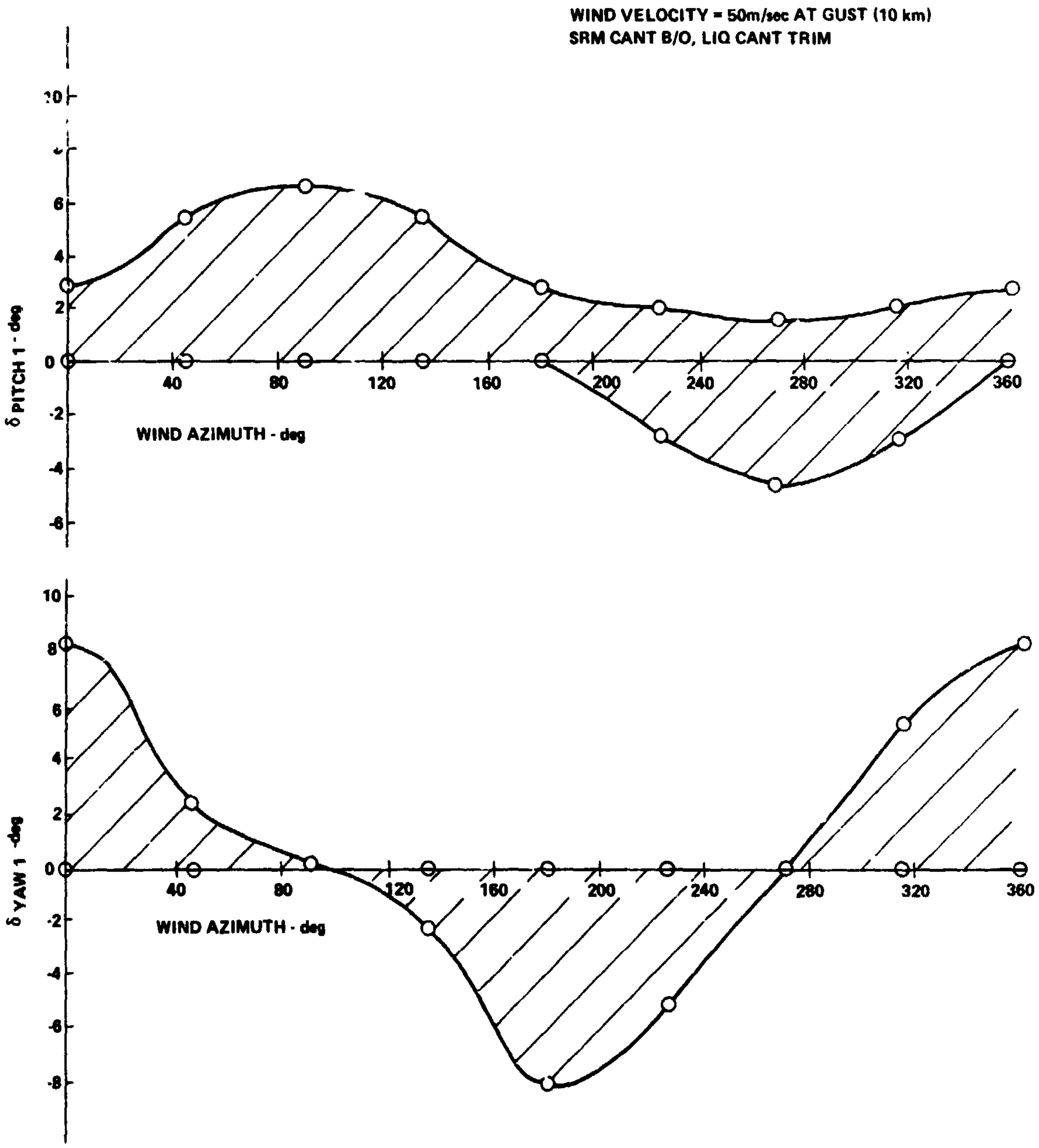


Figure 67. Wind azimuth variations.

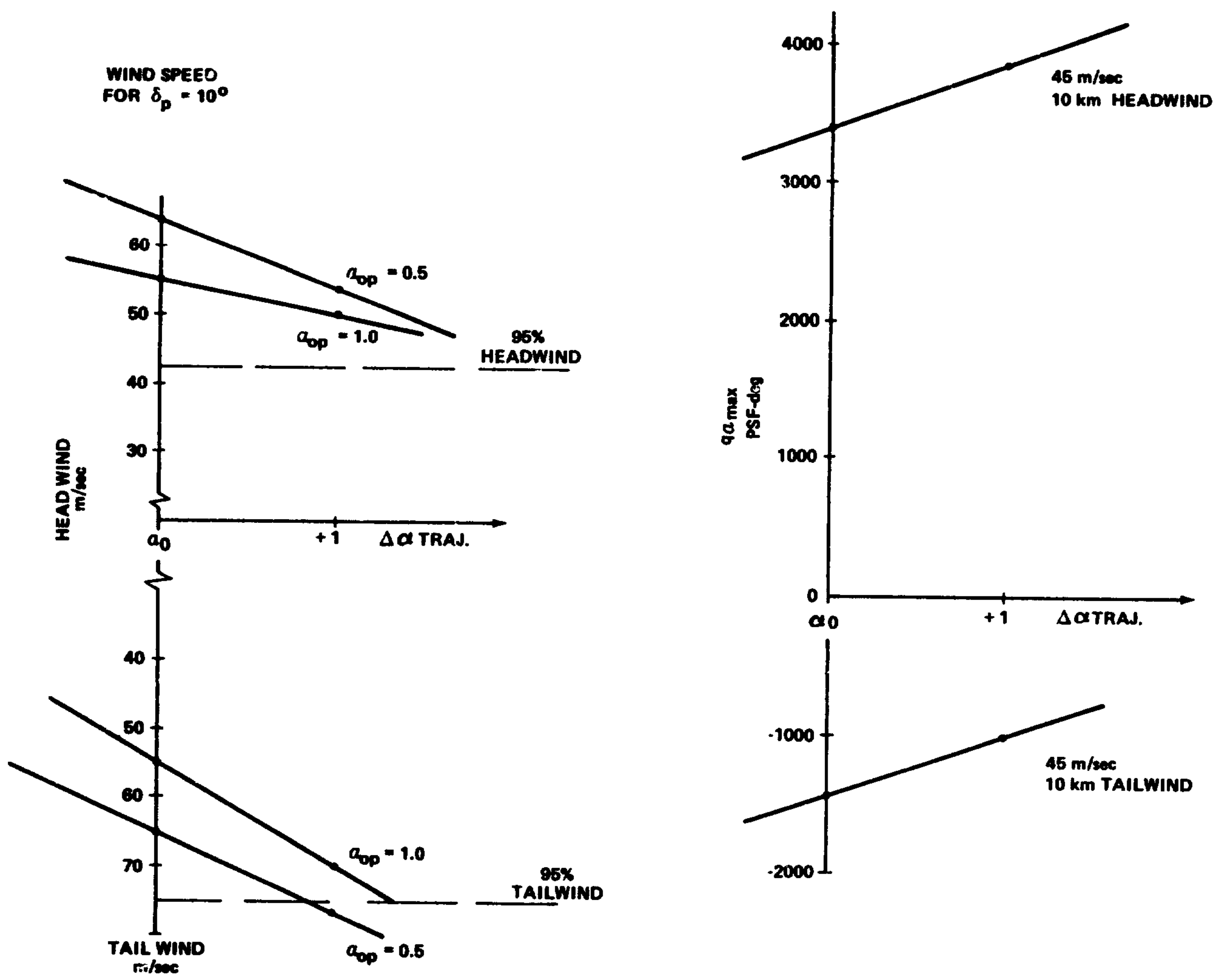


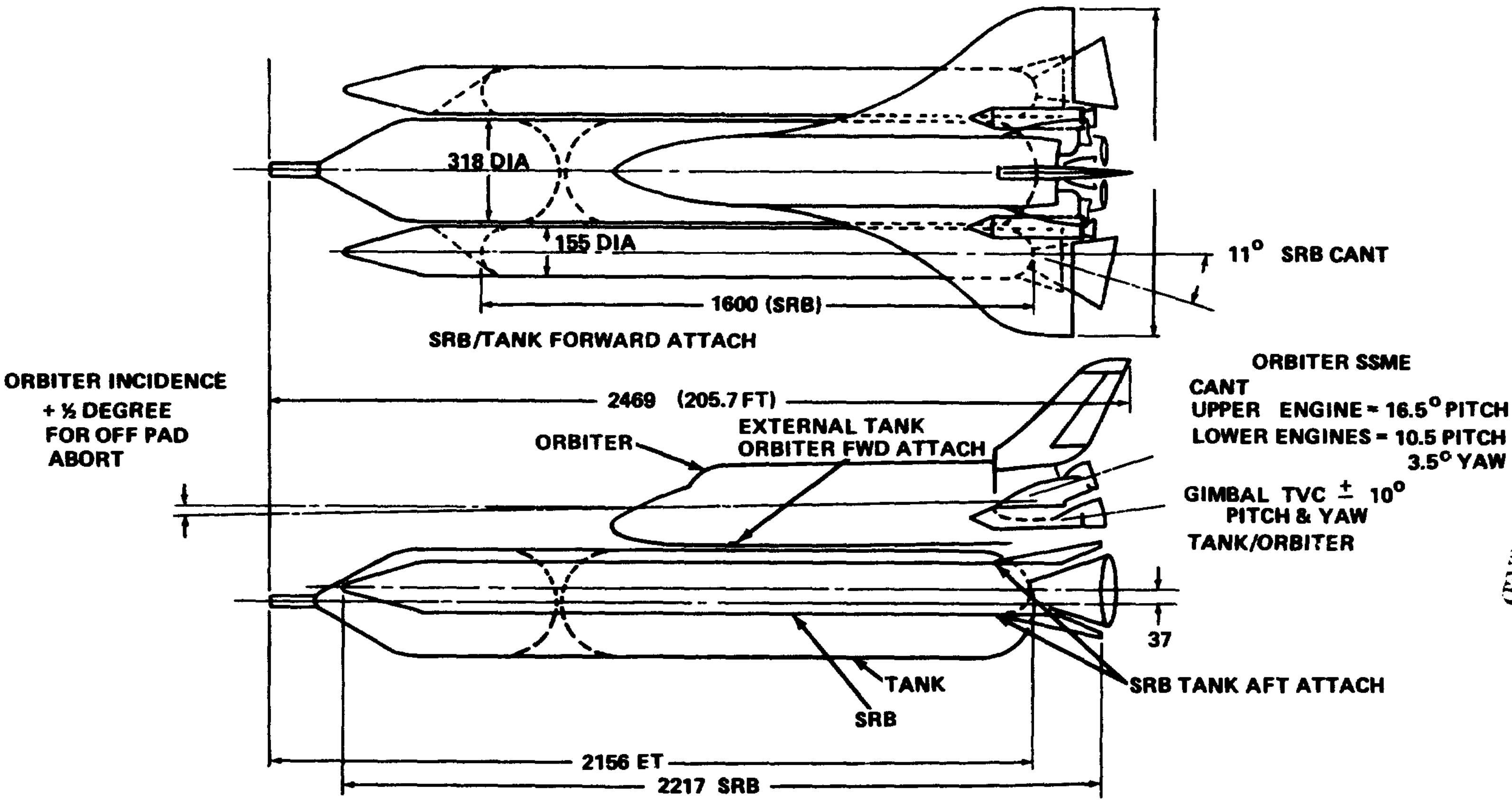
Figure 68. Trajectory effects on critical variables.

loads indicator, is increased for the trajectory for the headwind. It is still within an acceptable range, however. A 75 meter/second tailwind is the 95-percentile value rather than the 45 meter/second tailwind which is shown on the figure; the $q\alpha$ for a 75 meter/second tailwind, however, is not expected to exceed 3000 PSF deg. The $\alpha_0 + 1$ trajectory was selected for the 049 configuration studies.

APPENDIX

CONFIGURATION AND DATA

ATP BASELINE INTEGRATED VEHICLE



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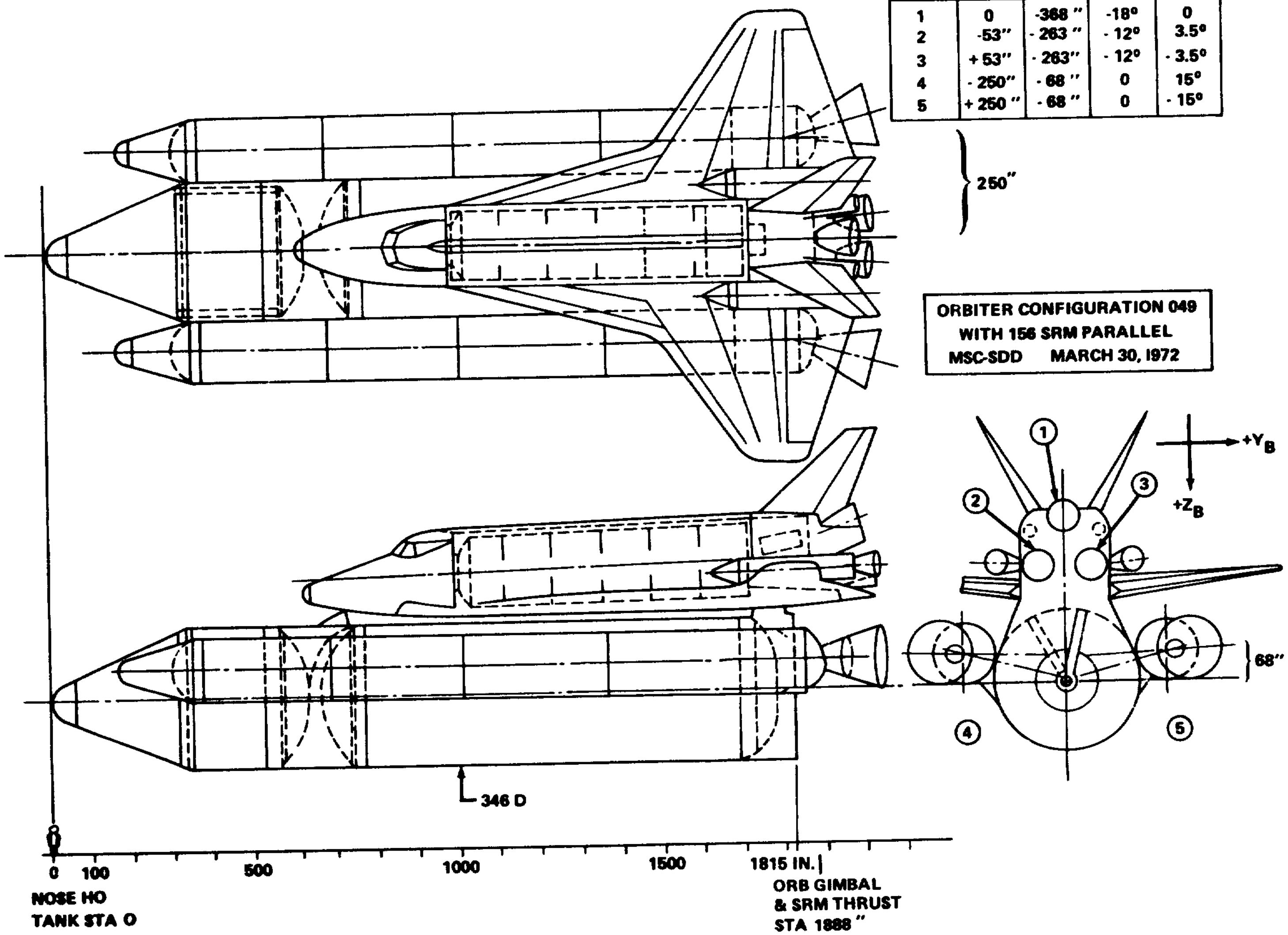
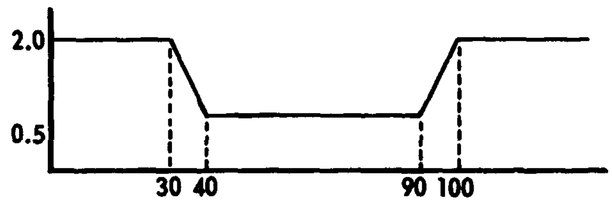


ENG	Y_E (ABOVE HO ℄)	Z_E (ABOVE HO ℄)	γ_p (CANT)	γ_Y (CANT)
1	0	-368"	-18°	0
2	-53"	-263"	-12°	3.5°
3	+53"	-263"	-12°	-3.5°
4	-250"	-68"	0	15°
5	+250"	-68"	0	-15°

Various combinations of gains were investigated with the optimum set dependent upon the particular variable of interest. The values listed below are typical of those required to achieve a good compromise.

		PITCH	YAW	ROLL	RUDDER
POSITION	a_0	2.0	.5[a]	.25	2.0
RATE	a_1	2.0	2.0	1.0	2.0
ANGLE OF ATTACK	b_0	0	.5[b]	-	-
INTEGRAL ERROR	a_{-1}	.1	-	-	-

a. SHAPED GAIN



b. $q = q/\hat{q}_{max}$

ATP CONFIGURATION GAINS – NO SRM TVC

	PITCH	YAW	ROLL	RUDDER ROLL	RUDDER YAW
POSITION	2.	.5	0.15[a]	4	4
RATE	2.	2.	0.5	4	4
ANGLE OF ATTACK	0	$.5\hat{q}$[b]	–	–	–

a. Shaped Gain

b. $\hat{q} = q/q_{max}$

NAR Shuttle #1 September 7, 1972

Time sec	Mass kg	χ_p deg	F/Eng N	X_{cg} m	Y_{cg} m	Z_{cg} m	I_R $Kg \cdot m^2$	I_y $Kg \cdot m^2$	I_z $Kg \cdot m^2$	F/Sol N
0	0.2454^{+7}	- 1.6	0.1668^{+7}	25.1		1.12	72.1^{+6}	477.9^{+6}	525.1^{+6}	0.1819^{+8}
5	0.2370^{+7}	- 1.6	0.1672^{+7}	25.2		1.125	68.9^{+6}	465.0^{+6}	509.8^{+6}	0.1821^{+8}
10	0.2286^{+7}	- 6.0	0.1685^{+7}	25.3		1.13	65.8^{+6}	451.5^{+6}	494.9^{+6}	0.1829^{+8}
20	0.2118^{+7}	-12.0	0.1736^{+7}	25.5		1.14	59.1^{+6}	425.7^{+6}	461.0^{+6}	0.1782^{+8}
30	0.1967^{+7}	-16.6	0.1811^{+7}	25.9		1.08	53.1^{+6}	400.0^{+6}	427.8^{+6}	0.1465^{+8}
40	0.1805^{+7}	-22.6	0.1890^{+7}	26.5		1.03	46.4^{+6}	364.7^{+6}	393.2^{+6}	0.1012^{+8}
45	0.1758^{+7}	-25.8	0.1923^{+7}	26.55		1.04	44.6^{+6}	356.6^{+6}	383.7^{+6}	0.9519^{+7}
50	0.1711^{+7}	-29.1	0.1956^{+7}	26.6		1.05	42.7^{+6}	348.4^{+6}	374.2^{+6}	0.1010^{+8}
60	0.1612^{+7}	-36.4	0.2007^{+7}	26.8		1.06	39.6^{+6}	334.9^{+6}	357.9^{+6}	0.1118^{+8}
70	0.1510^{+7}	-42.1	0.2043^{+7}	27.0		1.08	36.1^{+6}	321.3^{+6}	337.6^{+6}	0.1165^{+8}
80	0.1406^{+7}	-43.6	0.2066^{+7}	27.2		1.10	32.5^{+6}	303.7^{+6}	317.3^{+6}	0.1203^{+8}
90	0.1299^{+7}	-46.9	0.2078^{+7}	27.5		1.125	28.6^{+6}	286.1^{+6}	298.3^{+6}	0.1236^{+8}
100	0.1192^{+7}	-49.8	0.2085^{+7}	27.9		1.15	25.1^{+6}	271.2^{+6}	277.9^{+6}	0.1265^{+8}
110	0.1086^{+7}	-52.2	0.2088^{+7}	28.4		1.18	21.2^{+6}	252.2^{+6}	257.6^{+6}	0.1290^{+8}
118	0.9783^{+6}	-54.0	0.2002^{+7}	28.7		1.23	16.7^{+6}	235.9^{+6}	240.0^{+6}	0.1270^{+8}
128.5	0.9443^{+6}	-56.0	0.2090^{+7}	28.8		1.25	15.3^{+6}	230.5^{+6}	233.2^{+6}	0.451^{+7}

SELECTED SYSTEM SUMMARY

Mission		Mission 1 Due East			Mission 2 Resupply			Mission 3 Polar		
Payload Klb		65			43.1 W/O ABES/28.5 W/ABES			40		
		SRM	Orbiter	Ext. Tank	SRM	Orbiter	Ext. Tank	SRM	Orbiter	Ext. Tank
System GLOW	Klb	5410			5395			5371		
T/W @ Lift-Off		1.686			1.691			1.699		
Gross Wt(w/o abort)	Klb	3252	277.5	1782	3252	262.5	1782	3252	238.1	1782
Ascent Propellant	Klb	2829		1697	2829		1697	2829		1697
Dry Weight	Klb	423	170.0	66.3	423	170.0	66.3	423	170.0	66.3
Landing Weight	Klb		215.1			215.1			215.1	
End Boost Weight	Klb	423	277.2	84.9	423	262.2	84.7	423	237.8	84.7
OMS Propellant Usable	Klb		23.63			34.24			11.82	
RCS Propellant Usable	Klb		6.77			5.73			7.2	
$\bar{q}_{max}$	PSF	637			642			650		
$V_{staging}$ (Rel)	FPS	4795			4833			4874		
$\bar{q}_{staging}$	PSF	21.6			21.7			20.0		
$\gamma_{staging}$ (Rel)	Deg	28.9			28.57			28.9		
$h_{staging}$	KFt	167.5			167.5			170.0		
Time Staging	Sec	128.5			128.5			128.5		
Total Ascent Range	N. Mi	807.1			823.4			854.3		
Total Burn Time	Sec	544.9			546.5			550.7		
Engine Thurst	Klb	2X4089 SL	3X470 Vac		2X4089 SL	3X470 Vac		2X4089 SL	3X470 Vac	
Ideal ΔV (Total)	FPS	30,135			30,620		31,567			
To Separation		8377			8408		8461			
From Sep. to Insert incl. (FPR)		21,758			22,212		23,106			
WEIGHT SUMMARY					**DESIGN DATA**					
Wing	lb				Body Length	in		1975	1328	2184
Tail	lb				Body Volume	cu ft (ea)		20090	31036	86174
Body	lb				Body Wetted Area	sq ft (ea)			6238	
TPS	lb				Wing Area	sq ft				
Systems	lb				Exposed				2035	
Margin	lb	13,320		1368	Theoretical				3220	
Abort SRM's	lb		99,050		Tail Exposed Area	sq ft			435	
Resupply Mission only			1330		Total Wetted Area	sq ft (ea)		6421	11765	13997
OMS Kit (inert)	lb									
ABES (Dry)	lb		13,350		Body Diameter			156		318

APPROVAL

ASCENT CONTROL STUDIES OF THE 049 AND ATP PARALLEL BURN SOLID ROCKET MOTOR SHUTTLE CONFIGURATIONS

By Robert S. Ryan, David K. Mowery, Morris Hammer, and A. C. Weisler

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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